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Technical and Economic Feasibility of Integrated Video Service by Satellite

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Technical Support for Defining
Advanced Satellite Systems Concepts

Final Report for Task Order 5

Technical and Economic Feasibility of Integrated Video Service by Satellite

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Summary

Modern satellite technology can be used to implement a cost-effective, user-friendly, integrated video service which provides videophone and video conference service. This report gives a design for a system which allows the user to select a desired audience and establish the necessary links in much the same way one would establish a teleconference by phone. Important conclusions of this work are as follows:

- Three videoconference quality levels are expected to evolve: (1) 56 kb/s to 128 kb/s for videoconferences with reduced resolution involving a few people; (2) n x 384 kb/s for higher resolution motion video for small groups; and (3) business television will approach broadcast quality at rates between 2 and 8 Mb/s.

- The study focused on four integrated video applications: tele-medicine, virtual offices, CAD-CAM, and video retrieval. The integrated video traffic covering these applications is estimated to be 1,500 T1 lines or 2.3 Gb/s.

- System architecture provides full mesh connectivity to users through the use of small spot beams and on-board processing. To allow many users access to the network at a low bit rate, multifrequency TDMA at 2 or 6 Mb/s is used for the uplink and TDM at 54 Mb/s for the downlink.

- An on-board baseband switch interconnects the uplink and downlink coverage regions. The basic configuration of the on-board baseband processor includes demodulators, input processors, a baseband switch (high speed fiber optic ring), output processors, modulators, and a on-board network controller. The estimated mass of the on-board processor is 104 kg and power consumption is 874 W for a capacity of approximately 2.6 Gb/s.

- User duplex circuit costs are estimated to range from \$0.50/min for 128 kb/s, to \$1.52/min for 1 Mb/s, to \$6.88/min for 6 Mb/s circuits.

- Critical hardware and system engineering technologies which require development include: polyphase multiple carrier demodulators, FEC decoders, GaAs digital devices, bit synchronous TDMA system, design of the signaling packet, on-board network controller, and rain fade mitigation techniques.

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Chapter 1

Executive Summary

This chapter is organized as follows:

1.1 Background

1.2 Statement of Work

1.3 Organization of Report

1.4 Summary of Results

1.1 Background

Point-point video service, such as videophone, and point-to-multipoint video service, such as video conferencing, have been the subject of several overly optimistic technology forecasts. Though technically feasible, and to an extent operational today, neither service has met with widespread user acceptance. Two of the reasons for the deficiency are cost and user unfriendliness. With the availability of wideband fiber networks and the advent of high-power, intelligent satellites (like ACTS), it may be feasible to circumvent these two deficiencies.

What is needed is a feasibility study of using modern satellite technology, or more advanced technology, to create a cost-effective, user-friendly, integrated video service, which can provide videophone, video conference, or other equivalent wideband service on demand. What is envisioned is a system which would enable a user to select a desired audience and establish the necessary links in much the same way one would establish a teleconference by phone. No skilled auxiliary personnel would be necessary.

The contractor shall supply the necessary resources, manpower, and other equipment to perform the following subtasks under the Statement of Work.

1.2 Statement of Work

Subtask 1: Applicable Existing or Planned Video Standards

The contractor shall investigate current activities on digital video services by standard organizations and industry, and make technology assessments on the realization of various video service.

Subtask 2: Video Traffic Scenarios

The contractor shall develop several plausible traffic/network scenarios, which include traffic engineering for the earth stations as well as the satellite. The number of users, user activity, earth station capacity, and satellite capacity shall be specified based on acceptable blockage statistics, consistent with a demand assigned video system.

Subtask 3: System Architecture

The contractor shall develop a detailed system architecture based on advanced satellite and earth station technologies which would enable a cost-effective, user-friendly integrated video network. The architecture description shall include the following:

- Concept diagram,
- Detailed satellite and earth station processing block diagrams,
- Transmission system design parameters,
- Transmission formats (frame and burst structures, frame period, multiplexing schemes, etc.),
- Signaling channel formats and protocols,
- On-board control requirements, and

Table 1–1: Organization of the Final Report

Chapter	Contents
1.	Executive Summary
2.	Existing and Planned Video Standards
3.	Estimate of Traffic
4.	System Architecture
5.	Satellite Design
6.	User Costs
7.	Critical Technologies
A.	Video Practices
B.	Link Budgets
C.	Cost Comparison
D.	AIAA Paper: Feasibility of Integrated Video Service by Satellite

- Network Control Station (NCS) functions.

Subtask 4: User Costs

The contractor shall estimate the required user charges to insure a typical commercial rate of return for the integrated video service satellite network.

The charges shall be prorated amongst the users in an equitable fashion, and shall include a usage charge as well as a fixed charge. The method of allocating costs shall be subject to the approval of the NASA Technical Monitor.

Subtask 5: Critical Technologies

The contractor shall identify those technologies which are essential to the enablement of cost-effective, user-friendly integrated video services by satellite. The contractor shall submit a development plan for each of these technologies including estimates of schedule and resources to achieve a POC level of demonstration.

Subtask 7: Reporting

Reporting requirements include Interim and Final Briefings, Monthly Status Reports, and Final Report.

1.3 Organization of Report

Table 1-1 gives the organization of this Final Report by chapter. Chapter 2 describes existing and planned video standards, and Chapter 3 provides an estimate of the traffic. Chapter 4 describes the system architecture, and Chapter 5 gives the satellite design. Chapter 6 gives an estimate of user costs, and Chapter 7 describes the technology development plan.

There are four appendices. Appendix A describes current video practices, and Appendix B gives the link budgets for the Integrated Video satellite system. Appendix C provides a cost comparison of the Integrated Video system with Mesh VSAT and B-ISDN satellite systems. Appendix D is a copy of the paper presented on the Integrated Video system at *The 14th International Communications Satellite Systems Conference*, Washington, DC, March 1992.

1.4 Summary of Results

The summary of results is organized according to the chapters of this report:

- Existing and Planned Video Standards (Chapter 2)
- Estimate of Traffic (Chapter 3)
- System Architecture (Chapter 4)
- Satellite Design (Chapter 5)
- User Costs (Chapter 6)
- Critical Technologies (Chapter 7)

The reader is also referred to Appendix D which contains a copy of the paper based on this work.

1.4.1 Existing and Planned Video Standards

An overview of current television videoconference standards and equipment is made for the purpose of determining the service parameters for a future integrated video system. The conclusions are as follows.

Videoconference codecs will continue to gradually improve in quality and prices will continue to decline. The biggest change is expected to be in lower prices due in large part to VLSI and high speed digital signal processing chip development. ISDN and B-ISDN will also bring changes due to increased customer access to higher rate digital channels.

Three videoconference quality levels can be expected to evolve:

56 kb/s to 128 kb/s. The basic ISDN service will make 2B (128 kb/s) service widely available. Videoconferences involving a few people will be able to use this service. This service will support reduced resolution motion video, and higher resolution still and graphics. Expect that new higher resolution displays will display several channels in separate windows.

n x 384 kb/s. This will continue to be the primary service for small groups (6 to 10 people at each site). The increased bit rate allows higher resolution motion video and improved audio channel bandwidth. Codec manufacturers will eventually cross license improved coding to allow these to be incorporated into the standard.

Business Television. Current DBS development work will produce codecs with higher performance than currently available. Spatial and temporal resolution will approach broadcast quality at rates between 2.048 Mb/s and 8 Mb/s.

The large number of different standards currently found will disappear; customers will require adherence to widely accepted standards to increase the number of other locations that can be reached with visual communications.

1.4.2 Estimate of Traffic

The study focused on four integrated video applications:

Tele-Medicine. Remote diagnosis and analysis for second opinions, teaching and other purposes, transfer of medical records and images, remote database searches, remote operation room assistance, etc. Data rates will range from 64 kb/s to 6 Mb/s.

Virtual Offices. Inter-office meetings, client conferences, employee training, resolving program and production problems.

CAD/CAM. Real time changes to manufacturing process to match instantaneous needs of unique customer requirements. Allows limited custom product variations to come off a production line. Data rates will range from 128 kb/s to 6 Mb/s.

Video Retrieval. Employee training, production method reminders, videos of machine setups, application videos. Data rates will range from 128 kb/s to 2 Mb/s.

It is estimated that the integrated video traffic covering the above four applications will amount to a total of 1,500 T1 lines or to an aggregated information bit rate of 2.3 Gb/s. This will include a 1.4 Gb/s (900 T1 lines) network covering the application requirements for both Virtual Offices and CAD/CAM. Similarly, a 900 Mb/s (600 T1 lines) network will be needed for telemedicine which, in turn, will time share with the use of video retrieval. A heuristic approach is used to establish a first-order estimate of the demand for integrated video services as follows:

- By the year 2010 there will be 2.16 million United States corporations whose yearly sales exceed \$5 M. The assumption is that 1% of these corporations will require satellite delivered integrated video services at T1 rate for 1/2 hour per day. This results in a total of 900 T1 lines to be time shared by virtual Offices and CAD/CAM over a 12-hour day (i. e., 21,600 x 1/2 x 1/12 = 900).

- Similarly, there will be 1.2 million doctors in the United States by the year 2010. Out of this total there will be 24,000 radiologists and 640,000 specialists. The forecast assumes that 1% of the 664,000 doctors will use an average of one hour T1 per day. This results in 600 T1 lines to be time shared by telemedicine and video retrieval over a 12-hour day.

1.4.3 System Architecture

Figure 1-1 illustrates the basic concept for the integrated video network, where the satellite provides full mesh connectivity to users through the use of small spot beams and on-board processing. Typical applications are illustrated, including videoconferencing and point-to-multipoint video telecasts. The architecture provides for many similar network configurations simultaneously.

The network must allow flexible interconnection of user terminals, including point-to-multipoint capabilities. Many of the video services, such as video conferencing and video distribution, rely on point-to-multipoint or even multipoint-to-multipoint connection capabilities. A topology and signaling network to support these connections must be provided by the network architecture.

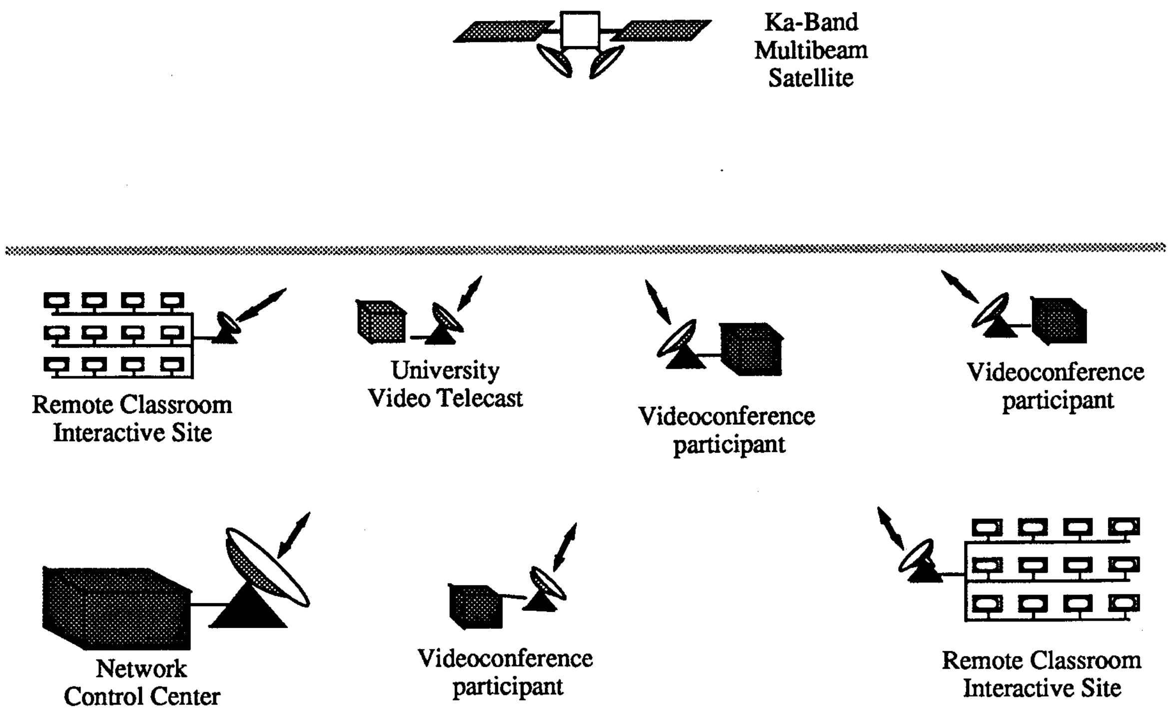

Figure 1–1: Integrated Video Network in which Satellite Provides Full Mesh Connectivity

Need for Full Mesh Topology

For integrated video, a full mesh topology is preferred for two main reasons.

i. Video services such as video conferencing are delay sensitive so multiple hops must be avoided.

ii. Traffic concentrations in this network for particular types of traffic (e. g. videoconferencing) will shift frequently, requiring a robust, distributed network with flexible resource allocation.

Although full mesh topology with many spot beams requires a more complicated on-board switch, the extra processing is necessary to adequately provide the network services. Although video telephone and video conference standards are still emerging, a few preliminary conclusions may be drawn that help to shape the design of an efficient architecture.

- In general, video service information rates will most likely be multiples of a base rate of 64 kb/s, up to approximately 6 Mb/s. The provision of these service rates is a key consideration in the network design.

- A flexible network control strategy must be provided to insure efficient and cost-effective use of the network and satellite resources.

Antenna Coverage

The selection of an antenna beam coverage pattern is driven by two competing factors:

- Use of many small spot beams is desirable for reducing the required terminal size of earth stations.

- More on-board processing is required to interconnect a larger number of beams.

For the integrated video network, small earth terminals are desired, the on-board processor complexity must be kept as low as possible, and the available bandwidth is limited. A coverage pattern that meets all of these requirements is shown in Figure 1-2. Twenty-eight fixed spot beams of $0.87°$ diameter provide continental U. S. (CONUS) coverage for the uplink and downlink; the coverage is symmetric. Isolation is achieved through a frequency reuse factor of 7, so that each beam area, which may have a bandwidth of up to

150 MHz, has a different frequency than its six neighboring beam areas. Therefore, a total system bandwidth of 1.1 GHz is used. This particular beam pattern is chosen to maximize antenna gain while also keeping the switching and hardware requirements on the satellite at a manageable level. As a result of using this size spot beams, terminal sizes as small as 1.2 m can be used.

Key Transmission Parameters

A summary of the key transmission parameters and architecture characteristics is given in Table 1-2. To allow many users access to the network at a low bit rate, multifrequency TDMA and TDM are used on the uplink and downlink respectively.

As described in ¶4.5, each uplink beam is dynamically allocated information rates of between 36 Mb/s and 108 Mb/s, in multiples of 36 Mb/s, based on capacity requirements. On the uplink, these 36 Mb/s blocks either consist of eighteen 2 Mb/s carriers or six 6 Mb/s carriers. Earth stations may access either a 2 Mb/s carrier or a 6 Mb/s carrier, depending on availability in a particular beam. On the downlink, two 54 Mb/s TDM carriers are used in each beam. The maximum information rate available in any uplink or downlink beam is 108 Mb/s. The frame structures for both of these formats are described in ¶4.8.

On-Board Baseband Processor

The design considerations identified the requirement for an on-board baseband switch to interconnect the uplink and downlink coverage regions. The basic functions performed by the on-board processor include the following:

- Demultiplexing/demodulation of uplink carriers
- Processing of the demodulated data
- Switching at baseband to the destination ports
- Processing of the switched data for remodulation
- Remodulation on downlink carriers

The control system of the processor is also responsible for monitoring and controlling the processor subsystems and for processing channel requests. This control system interacts with a network control station in one of the beams.

Figure 1-3 shows the basic configuration of the on-board baseband processor. The block diagram includes demodulators (shown as MCDs or multicarrier demodulators), input processors, a baseband switch (high speed fiber optic ring), output processors, modulators, and a on-board network controller. The estimated mass of the on-board processor is 104 kg and power consumption is 874 W for a capacity of approximately 2.6 Gb/s.

Critical Design Issues

Critical design issues are identified as follows:

Low-Power MCD. The most critical element in the design appears to be a low-power consumption multicarrier demodulator. The MCDs consume 65% of the power in the baseband processor. Intensive development efforts to reduce the MCD power consumption to the range of several watts is highly recommended.

Bit Synchronous System. In a multicarrier access environment, a bit synchronous system improves frame efficiency and simplifies network design. However, the MCD is required to measure a phase error with an accuracy of a small fraction of a symbol period. It also requires the user terminal to perform accurate timing correction. Alternate techniques to implement a bit synchronous system at these carrier rates should be investigated, and a proof-of-concept model to demonstrate its feasibility should be developed.

Multicarrier Viterbi Decoder. A high-speed multicarrier Viterbi decoder also requires development. Because a convolutional decoder incorporates memory in its decisions, a large constraint length code is difficult to implement at high speeds. The rate 1/2 code suggested here may be replaced by another code which offers higher coding gain and ease of implementation.

Signaling and Control Issues. Numerous signaling and control issues discussed in Chapter 4 must be considered. Further study is recommended in the area of autonomous network control, as well as in areas concerning the baseband switch (such as optimal buffer sizes and packet transmission formats). Finally, multicast signaling protocols must be developed to meet the needs of integrated video users.

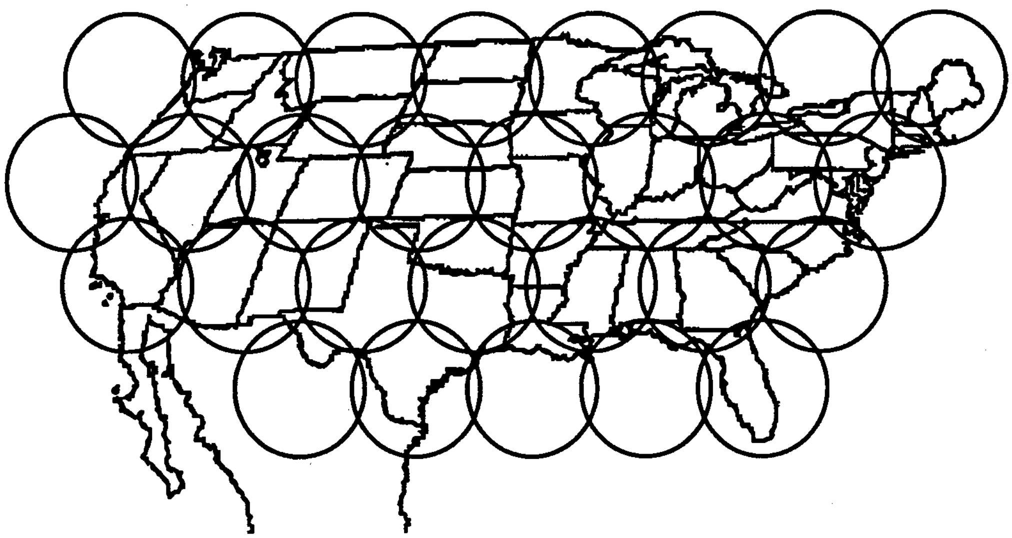

Figure 1–2: 28 Fixed Spot Beams of 0.87° Diameter Cover CONUS for Both Uplinks and Downlinks

Table 1–2: System Parameters for Integrated Video System Design

System Parameters	Uplink	Downlink
Frequency	30 GHz	20 GHz
Number of beams	28 fixed	28 fixed
Access method	TDMA	TDM
Modulation	D-QPSK	QPSK
FEC convolutional coding	R=1/2	R=1/2
Information bit rate per beam	36, 72, or 108 Mb/s	54 or 108 Mb/s
Transmission bit rate per beam	72, 144, or 216 Mb/s	108 or 216 Mb/s
Bandwidth allocation per beam	150 Mb/s	150 Mb/s
Frequency reuse pattern for isolation	7	7
Total system bandwidth required	1.1 GHz	1.1 GHz
Carrier bit rate (information)	2 or 6 Mb/s	54 Mb/s
Capacity of MCDs	36 Mb/s	–
Number of MCDs	84	–
Number of carriers/beam (maximum)	30	2
Total number of available carriers	840	56
Beam capacity (maximum info rate)	108 Mb/s	108 Mb/s
Satellite capacity (1 satellite)	2.6 Gb/s	2.6 Gb/s
Satellite transmit power per 54 Mb/s channel	–	13 W
Total satellite transmit power (49 channels)	–	637 W
Earth station diameter	1.2, 1.8, 3 m	–
Earth station transmit power	4 – 12 W	–

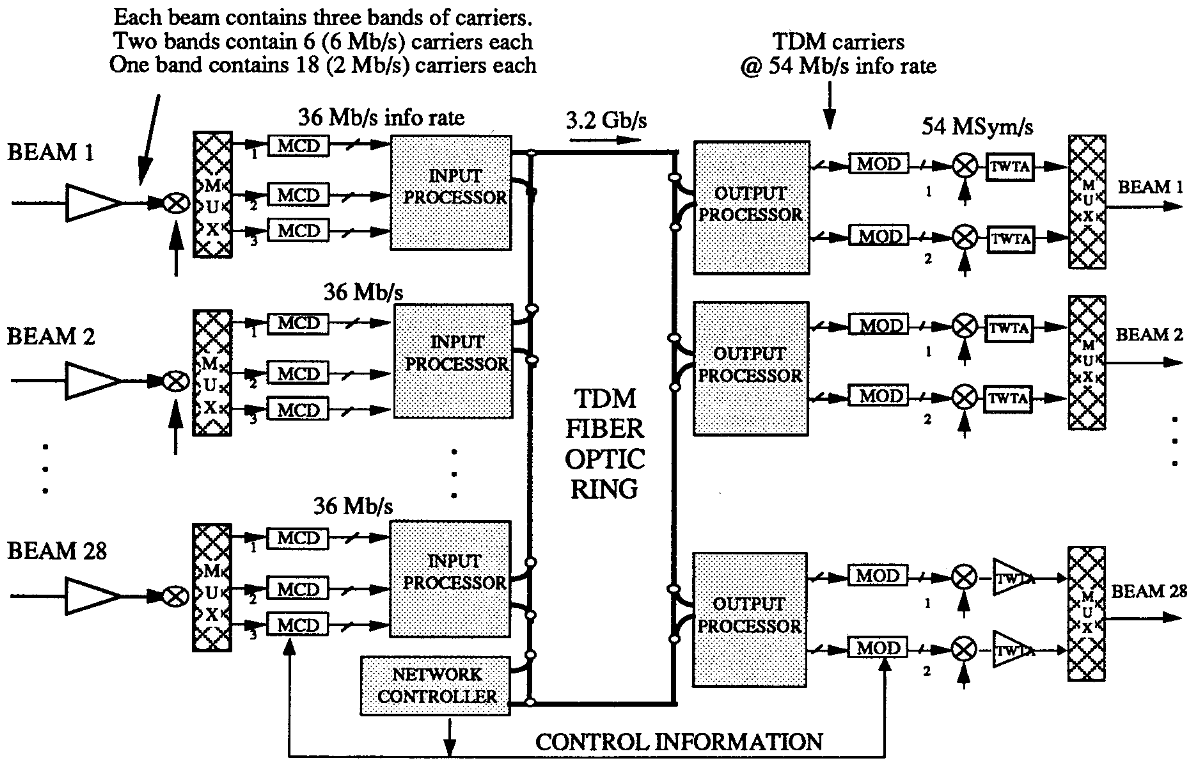

Figure 1–3: Configuration of On-Board Baseband Processor

1.4.4 Satellite Design

The approach is to evolve the existing satellite design (1990 technology base for 1995 launch) to the Integrated Video satellite design which assumes a year 2000 technology base for a year 2006 launch. Technology advances are assumed in the propulsion and power subsystems. Ion propulsion thrusters are used to reduce the mass of on-orbit station-keeping fuel and thus enable longer lifetimes. Lower mass batteries and solar cells allow greater payload mass.

Table 1-3 summarizes the payload electronics mass and power for the 2.6 Gb/s payload. Major components contributing to the payload mass and power are the upconverters and downconverters, the multi-carrier demodulators (key component of the baseband processor in terms of mass and particularly power consumption), and the 13 W TWTAs.

The bus design is based on the Loral FS-1300 series which is presently in production for commercial applications such as Superbird, Intelsat-7, and N-Star. The result is a 1,727 kg dry (1,887 kg wet) satellite mass with a 589 kg M-VSAT payload (antenna plus communication electronics) and 4.3 kW end-of-life power. Figure 1-4 shows the satellite on-orbit configuration.

In spite of the addition of a 104-kg 874-W baseband processor and only 637 W of RF transmit power, the Integrated Video satellite has a total capacity of 2.646 Gb/s comprised of 504 2-Mb/s channels plus 273 6-Mb/s channels. In addition there is flexibility to simultaneously interconnect channels among beams in the point-to-point, multicast, or broadcast modes.

This performance is due to the following design factors:

- Regeneration on the satellite gives a 3-dB link performance advantage.
- Spot beams give more efficient use of satellite power.
- Convolutional coding on uplinks and downlinks gives 5 dB performance improvement.
- An OMJ for combining TDM downlinks in the same beam saves 1.5 dB compared to an output multiplexer.
- BPSK is assumed to be used on downlinks, which saves 1.2 dB relative to QPSK due to less modem

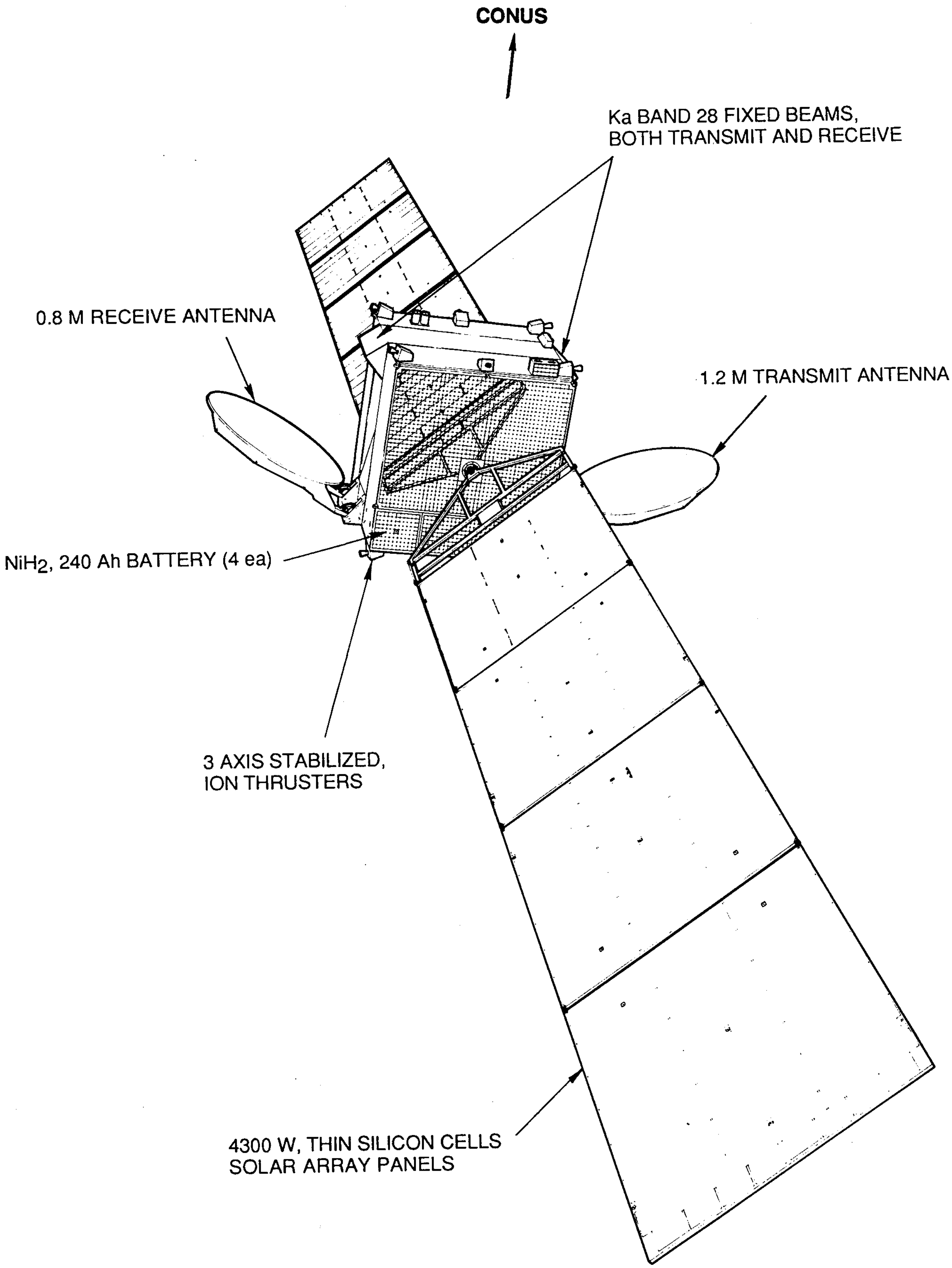

Figure 1–4: Integrated Video Satellite On-Orbit Configuration

Table 1–3: Payload Electronics Mass and Power Breakdown

Equipment	Mass (kg) Qty.	Mass (kg) Unit	Mass (kg) Total	Power (W) Qty.	Power (W) Unit	Power (W) Total	Comments
Baseband Processor							
MCDs – 2 Mb/s carriers	28	0.7	20	28	9.0	252	
MCDs – 6 Mb/s carriers	56	0.4	22	56	5.6	314	
Input processor	60	0.4	11	28	3.7	104	
Switch fabric & support	1	1.0	1	1	10.0	10	
Output processor	28	0.4	11	28	3.0	84	
Modulators	56	0.2	8	56	0.2	11	
Network Controller	1	1.1	1	1	12.0	12	
Timing source	2	1.5	3	1	3.0	3	2–1 redundancy
DC/DC converter	2	7.0	14	1	83.4	83	90% efficiency
Structure	1	12.0	12				
Subtotals			104			874	
Low noise amplifiers	42	0.4	26	28	1.2	34	6–4 redundancy
Receivers (28/4 GHz)	42	1.8	76	28	8.0	224	6–4 redundancy
Input demultiplexers	28	1.5	42				3 channel
Upconverter (4/20 GHz)	70	1.1	77	49	3.0	147	10–8 redundancy
TWTA/EPC (13 W, 20 GHz)	70	1.6	112	49	36.1	1,769	10–8 redundancy, 36% eff.
Output filter	56	0.2	11				
Master LO	2	5.0	10	1	6.0	6	2–1 redundancy
DC/DC convertor (upconverter)	35	0.4	14	25	6.0	150	2–1 redundancy
Redundancy switches			34				
Waveguide and coaxial cable			9				
Beacon transmitters	2	2.0	4	1	15.0	15	2–1 redundancy
Margin			25			159	5% margin
Totals			535			3,378	Mass (kg), Power (W)

loss and co-channel interference loss.

- FDMA uplinks (and TDM/FDMA uplinks) give the additional advantage of allowing use of smaller earth terminals.

1.4.5 User Costs

User costs are developed based on the schedule in Figure 1-5 for the Integrated Video system implementation. Table 1-4 summarizes the space segment costs in 1992 dollars, and Table 1-5 gives the ground terminal costs for two sizes of terminals. The full set of assumptions for developing these costs is given in Chapter 6.

Total user costs are derived by a two step process. First the space segment and network control costs for a simplex circuit are derived. Second, the user terminal costs are added to the space/control costs to obtain the total user cost per minute of circuit use.

Table 1-6 gives the duplex circuit cost for different circuit sizes for the small (1.2 m), medium (1.8 m), and large (3 m) users. Overall system utilization is assumed to be 15%, and ground terminal usage is assumed to be 4 hours per working day. A 5 minute "videophone" duplex call at 128 kb/s (two-way) between two small users would cost $2.50.

A 1-hour video conference between two large users at 6 Mb/s would cost $396 (requires 4 simplex half circuits where a half circuit is from the ground to the satellite or vice versa). A 1-hour video conference between three locations for large users at 6 Mb/s would cost $891 (requires 9 simplex half circuits). However, 1-hour video conference between four locations for large users at 6 Mb/s would cost $1,584 (requires 16 simplex half circuits).

Appendix C presents a cost comparison between the

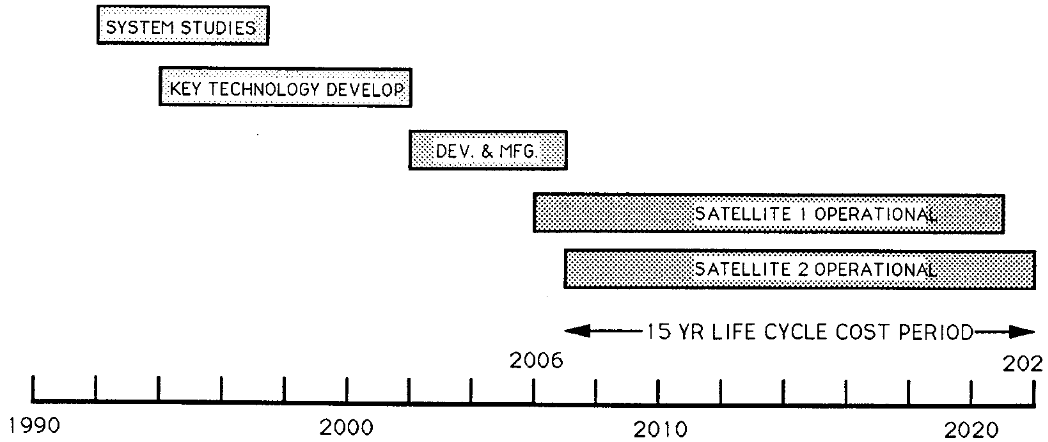

Figure 1–5: Schedule for Integrated Video Satellite System Implementation

Table 1–4: Space Segment Costs, 1992 $M

Cost Category (2 satellites on orbit)	Life Cycle Cost	Annual Cost at 18%
Satellite cost (2)	560 M	
Launch Cost (2)	248 M	
TT&C Support (2)	15 M	
Launch Insurance (16%)	157 M	
Total Costs	$980 M	$192 M/yr

Table 1–5: Ground Terminal Annual Costs (1992 $)

Terminal Type and Cost	Lease Cost ($/yr)	Maintenance Cost ($/yr)	Total Cost ($/yr)
Small (1.2 m), $35,000	7,000	3,500	10,500
Medium (1.8 m), $45,000	9,000	4,500	13,500
Large (3 m), $55,000	11,000	5,500	16,500

Table 1–6: User Costs for Duplex Circuits

User Size (m)	Total User Costs ($/min), Duplex Circuit for Data Rate (Mb/s)					
	0.128	0.256	0.512	1.0	2.0	6.0
1.2	0.50	0.62	0.88	1.42	2.46	–
1.8	0.60	0.66	0.98	1.52	2.56	6.78
3.0	0.70	0.82	1.04	1.62	2.66	6.88

Integrated Video satellite system and two other concepts, the B-ISDN and Mesh VSAT systems.

1.4.6 Critical Technologies

The technologies which are critical or enabling to the application of satellite delivered Integrated Video service are identified and described in two categories, hardware development and systems engineering development.

Hardware Developments:

Polyphase multiple carrier demodulators (MCDs) operate with uniform carriers (either at 2 or 6 Mb/s) over a 36 MHz band. The power consumption of each MCD is targeted to be less than 10 W.

FEC decoders operate at 100 Mb/s, using Rate 1/2 convolutional code with a 16 state code. The coding gain is expected to be 5.4 dB at an BER of 10^{-6}.

GaAs digital devices for fiber-optic interfaces with a speed of 400 Mb/s and a power consumption about 0.05 mW/gate.

Systems Engineering Developments:

Bit synchronous TDMA system. The MCD design has less mass and power consumption with a bit synchronous system. A study of feasibility, design approach, performance assessment via computer simulation, and cost-benefit tradeoff is required. This study must occur before the MCD development is started.

Design of the signaling packet for transmit acquisition. To determine the exact format and size of the signaling packet assuming that the guard time between TDMA frames is 60 μs and the timing acquisition window is 170 μs.

On-board network controller with a flexible strategy. The network controller must be fast and flexible enough in changing multipoint connections, service quality, and channel bandwidth.

Rain fade mitigation technique. Effective techniques must be developed to combat excessive propagation loss by a combination of resource allocation methods through an increase of EIRP, a decrease of information bit rate, and/or the inclusion of a special FEC codec in the affected transmission channel.

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Chapter 2

Existing and Planned Video Standards

This chapter presents an overview of current television videoconference standards and equipment, and is organized as follows:

2.1 Standards Activities gives an overview of current international videoconference standards.

2.2 Teleconference Components is a short review of videoconference operations.

2.3 Digital Video Transmission Services summarizes videoconference transmission services.

2.4 Conference Room Facilities are described.

2.5 Videoconference Codecs are described.

2.6 Still Image Transmission equipment is described.

2.7 Predictions for Future Equipment and Standards are made.

References are given at the end of the chapter. Appendix A, Video Practices, summarizes a wide range of video practices from high definition television to low resolution, low rate services.

Videoconference systems can be placed in four categories:

Business television systems use either analog transmission links or high rate digital links (1.5 Mb/s to 44.7 Mb/s) for two-way video and audio or one-way video with return audio. These are often point-to-multipoint links used for sales meetings or remote education. These systems provide full broadcast television resolution and motion capabilities. Spatial resolution is 640 x 480, at 30 frames per second (fps) [1].

Fractional T1 to T1 systems use digital transmission at rates from 384 kb/s up to 1.544 Mb/s. These codecs generally operate with signals at approximately half the spatial resolution (e. g. 256 x 240) and reduced temporal resolution of 10 to 15 frames per second. Although manufacturers call these "full motion" codecs, the ability to display motion is limited by both the temporal sampling rate and the coding used to reduce the bit rate. These systems generally are capable of displaying head and shoulder views of small groups with low to moderate motion.

56 kb/s to 128 kb/s video codecs achieve lower transmission rates by further reducing the spatial and temporal resolution, and by additional processing. Some systems specify the "quarter image format" and reduce the horizontal and vertical sampling rates of the previous group by half. Temporal resolution may be further reduced. These are often used for personal teleconferences with only one or two people appearing on the screen at a time.

Still video codecs combine still frame transmission and two-way audio. Resolution and accuracy are similar to the business television class. Transmission can use digital rates to 128 kb/s, or can use normal analog voice circuits.

The high rate codecs are generally less expensive, and deliver video signals with quality that is familiar to most viewers. Codecs operating at low to moderate rates at one time were quite expensive, but several recent products have been announced in the $10 K to $30 K range.

Developments outside the teleconference field will soon increase the number of options. The emerging DBS technology development is expected to provide codecs that can be used in the business television services. These codecs promise higher resolution and increased motion handling capabilities in the 3 Mb/s to

15 Mb/s region. The associated mass production will make decoders available at very low prices. These new codecs,used with B-ISDN transmission facilities, are expected to provide higher quality links at reduced costs.

Video conference meeting rooms may be dedicated facilities with built-in components, multiple use rooms served by a roll-around cart, an office served by portable equipment, or a workstation. Meeting rooms may be public or private. Both should be local, minimizing the travel time from office to meeting room. Private rooms may offer convenience in location and scheduling, and can be designed specifically for an organization's needs.

A final area is telecommunications access. All local operating companies supply services suited to video-conferencing, but only in limited areas. Access to 56 kb/s circuits is increasing, but access to T1 connections (1.544 Mb/s) is slow. Customers are served by satellite transmission with wide availability of rates.

2.1 Standards Activities

Standards are important because they assure that equipment from one manufacturer will communicate with that from other manufacturers. The following standards are being developed in the CCITT.

2.1.1 CCITT

CCITT Fascicle III.6 [2], "Line Transmission of Non-Telephone Signals", contains a number of evolving recommendations for videoconference equipment and transmission facilities. Since publication in 1989, many of these have had extensive revisions under consideration in the working groups.

H.100 Visual telephone systems

H.110 Hypothetical reference connections for videoconferencing

H.120 Codecs for conferencing using primary rate (1.544 Mb/s & 2.048 Mb/s)

H.130 Frame structures for interconnection of visual codecs

H.140 Multipoint international videoconference system

H.200 Framework for recommendations for audiovisual services

H.221 Frame structure for 64-kb/s channel ...

H.222 Frame structure for 384 kb/s to 1,920 kb/s channels

H.261 Codec for audiovisual services at $n \times 384$ kb/s

Recommendation H.261 currently applies to codecs for fractional T1 or T1 services. The importance of this recommendation can be seen in the codecs now being produced by Eyetel, Compression Labs, PictureTel and NEC. All offer either hardware versions or software versions of codecs to the H.261 standard.

This is the area with the most standardization activity. This recommendation is still incomplete, but forms the basis for a number of offerings from different manufacturers.

The recommendation currently includes a series of codecs operating at rates of $n \times 384$ kb/s, where n ranges from 1 to 5. The recommendation also recognizes the need to work at lower rates, and in the future will define codecs of $m \times 64$ kb/s, where m is still to be determined. Since several manufacturers already are offering $m \times 64$ kb/s codecs, this should be included in the next version of the recommendation.

The source coding algorithm uses inter-picture prediction to utilize temporal redundancy, and transform coding of the remaining signal to reduce spatial redundancy. Provisions for motion compensation are provided, and will be added in future versions.

Audio is encoded using mode 2 of Recommendation G.722 and occupies a 64 kb/s time slot. Recommendation H.221 defines the sharing of the audio slot with control and identification information.

The recommendation covers interworking between 525 and 625 line standards. A common standard has the following parameters:

- Non-interlaced pictures at 29.97 frames per second
- Component video, Y, Cr and Cb color difference signals.
- Black level = 16, White level = 235
- Peak color difference = 16 and 240, Zero color difference = 128.
- 288 lines per picture, 352 pixels per line in orthogonal arrangement.
- Color difference components are 144 lines per picture, 176 pixels per line.

The non-interlaced scan is produced by a converter that accepts a standard 525 or 625 line interlaced signal and produces the common standard. At the decoder, the codec converts from the common standard to display equipment.

2.1.2 U. S. Standards Activities

ANSI committees usually are the forum for U. S. companies, and are often the basis for a U. S. recommendation to the CCITT. Information for ANSI recommendations was not available for this report. The Electronic Industries Association also sponsors committees for definition of new equipment. The Advanced Television Standards Committee (ATSC) is sponsored by the Federal Communications Commission, and has been working to define a new television standard for use in the United States. This work has led to a set of field trials of prototype equipment during the 1991–92 period (see Appendix A). When the new standard is approved, it is expected to be used in computer displays as well as in new television equipment. The Department of Defense is also expected to require adherence to this standard for new equipment.

2.1.3 CCIR

Recommendation 601. Encoding parameters of digital television for studios.

This standard specifies digital coding for television signals that covers both 525 and 625 line systems. The system is based on encoding the luminance channel at 13.5 MHz, and encoding the two color difference signals Cr and Cb at 6.75 MHz (4 2 2 sampling) using 8-bit samples. This is primarily a color component specification defined for use within studios, for production recording, and for distribution of signals to another studio where additional editing may be performed.

A number of different standards for sampling rates are included. For television production the 4 2 2 system is used; standard broadcast uses 4 1 1 sampling. Recommendation 601 describes conversions from one sampling standard to another, and conversions between NTSC, PAL and SECAM.

2.2 Teleconference Components

A videoconference is generally a two-way service with the capability of transmitting live or static pictures and associated speech, and may include more than two locations. Figure 2-1 shows the minimum equipment involved in a videoconference with two sites. Each site is equipped with a camera, monitor, microphone, and speaker. The monitors display the video from the other site. Most videoconferences have additional facilities.

CCITT Recommendation H.100 describes basic facilities that should be included in terminal design.

- Transmission of live pictures with head and shoulders of one person, or of a small group of persons with moderate definition.
- Transmission of associated speech.
- Transmission of graphics information within the capabilities of display equipment.
- Video conference service with or without the use of split-screen techniques.

The cameras and displays in a teleconference are normally compatible with the local broadcast television standard, e. g. NTSC, PAL, or SECAM. The codecs accept and deliver signals compatible with this equipment, but normally do support the full quality of the broadcast standard.

Figure 2-2 shows a comparison of the display capabilities of various television standards. This figure shows the size of the screen when viewed from the critical viewing distance: that is the distance where the eye can just perceive the finest detail in the picture. Moving closer makes the scan lines become more visible, moving further away causes loss of detail by the visual system. The numbers by each standard are the number of scan lines, the field rate, and the interlace factor. Appendix A describes these in more detail.

The critical viewing distance for NTSC video is between 4 and 6 times the picture height. The critical viewing distance for the typical videoconference codec is between 8 and 12 times the picture height. Since monitors are measured by the diagonal, and the NTSC picture has a width:height ratio of 4:3, the picture height of a 25 inch monitor is 15 inches. The critical viewing range for a video conference picture is 10 to 15 feet, even though it is displayed on an NTSC monitor.

Figure 2-2 also shows the advantages of an HDTV screen (NHK version). The resolution is higher, and the width to height ratio is increased to 5:3. The viewer is presented with a wide screen display that is equivalent to 5.7 NTSC screens. The Advanced Television

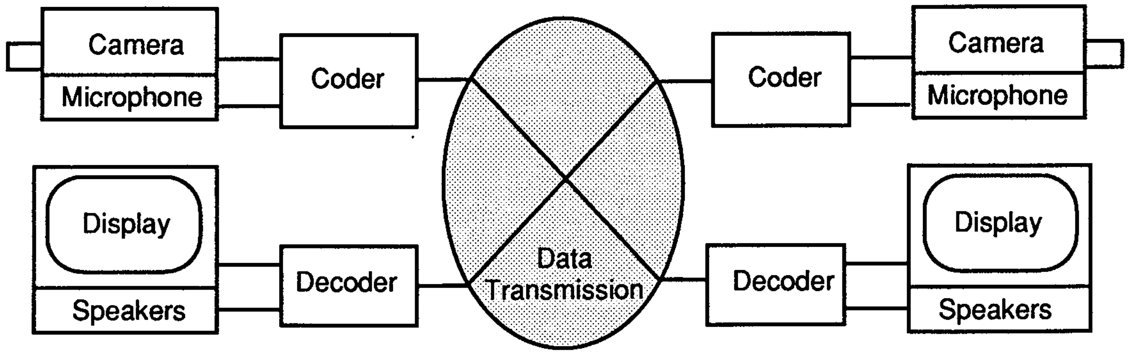

Figure 2–1: Basic Teleconference Equipment

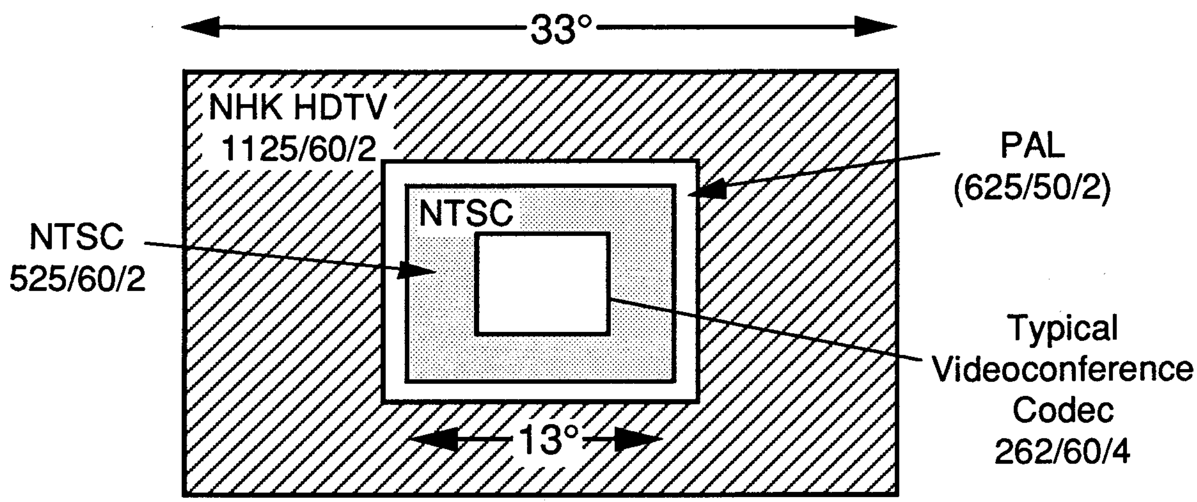

Figure 2–2: Television Formats Viewed at Critical Distance

Standards Committee is currently working to define the next generation television standard. The NHK standard shown in Figure 2-2 is one of the candidates being evaluated. The standard that will evolve from the current efforts is expected to be used in future displays, and could be used for display of graphic information, or for mixed displays with picture-in-picture that show a motion video window inset into a larger graphic display.

Since teleconferences often include small groups, and simplified teleconference operation are desirable, Recommendation H.100 describes several alternatives for displays of small groups without needing a trained, full-time operator. One of these is a split screen technique where two cameras are used as shown in Figure 2-3. Pictures from the two cameras are combined to produce a split screen display with the signal from one camera on the top of the display, and the signal from the other camera is shown at the bottom of the display. This makes better use of the display area while minimizing the need for operator actions.

After the room arrangement has been determined, techniques for handling lighting and audio then need to be specified. A teleconference produces a set of conflicts that are not present in normal TV broadcast. The scene must have sufficient illumination for camera operation, but the illumination at the monitor must be low enough to allow the picture to be viewed. Microphones must pick up the voice from any participant in the studio, and all participants must be able to hear the audio from other locations. Unfortunately, a microphone also picks up sounds from the local loudspeakers, and these can be transmitted back to the other location. This echoed signal is delayed by the round trip satellite delay plus any processing in the codecs.

These requirements for lighting and control of audio echo are addressed in a number of approaches. Special

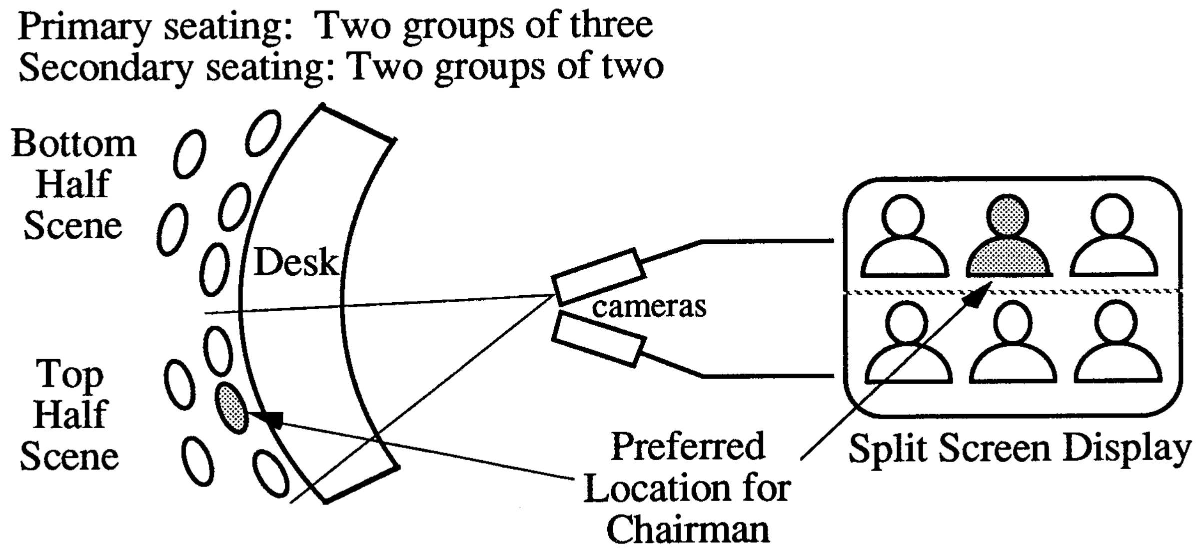

Figure 2–3: Studio Plan View

room lighting can increase illumination on the participants and reduce the glare on the display. Acoustic room treatment reduces the level of coupling between speaker and microphone. Additional audio processing can include "push to talk" operation, acoustic echo cancellers designed for use in studios, or individual ear sets for each participant instead of speakers. Of these options, the most desirable from the view of the participant is echo cancellation.

Another option for teleconferences with multiple participants includes a camera with pan and zoom capability. The selection of participant can be directed by the conference chairman, or can be performed by audio detection. Both increase the complexity of conference control. Design of a simple control system for the conference chairman is difficult - especially for control of equipment at the other end. Audio control can be unreliable - the wrong participant might be selected or too frequent switching can be objectionable.

2.2.1 Codecs

The idea of a two way audio visual conference was conceived as early as 1927 at Bell Labs. An early version of Picturephone, a desktop telephone with video was shown in 1964, but never made it into the market place. Bell introduced the Picturephone Meeting Service featuring video-equipped meeting rooms in 1970, but discontinued them in 1985 due to lack of customer interest. (One reason is that there were only a few rooms at the time.) Since that time, several companies have continued development of these systems.

Most full resolution systems require large bandwidths or large bit rates. Much of the earlier work was aimed at two markets:

i. High rate codecs serving the needs for program distribution or news gathering for broadcasters.

ii. Low rate codecs that can use T1 and fractional T1 connections for lower communications cost.

The evolution of these systems shows one of the tradeoffs between coding to reduce transmission costs, and simple codecs to reduce equipment cost. One key to reduced equipment cost is large scale production. To date, there have been few applications that demand a large number of low-rate codecs for full resolution applications. Many of these applications currently require only a small number of hours for operation, and frequently use standard analog signals.

Most high rate transmission currently uses either full or half of a satellite transponder for full motion signals. Most transmission uses FM modulation, for either a 30 MHz bandwidth or a 17.5 MHz bandwidth. The television signal formats are either composite or MAC (multiplexed analog components). Work continues on coders operating either at 45 Mb/s and 32 Mb/s, the two D3 hierarchies. A recommended standard for 32 Mb/s operation is nearing the final steps.

There is currently considerable interest in moderate rate coders for use in either DBS (direct broadcast satellites) or in cable distribution. Both DBS and cable systems want to increase the number of channels that can be received, and to reduce problems with received noise or multipath reception. In time, these will result in inexpensive equipment capable of increased spatial and temporal resolution (compared to the low rate codecs).

The 1990 costs per hour for digital transmission facilities is shown in the Figure 2-4. This shows the cost advantages of 56 kb/s transmission facilities. Perhaps of even greater importance is the access to 56 kb/s circuits.

2.2.2 Ancillary Equipment

Ancillary equipment is often also desirable, such as a document reproduction. Most broadcast standards do not support high quality of documents, and videoconference codecs further reduce the resolution in the signal. Some systems introduce additional cameras for document transmission. These are normally still cameras, and provide increased spatial resolution. This camera may use the same TV standard (e. g. NTSC) or may be a high resolution system for high quality document display. Either approach increases the complexity of the teleconference since additional camera (or scanners) and display must now be introduced. Additional channels are needed for transmission, and additional control capabilities are needed.

2.2.3 International Compatibility

International compatibility requires compatibility with video standards, codecs, session control, ancillary equipment, and transmission facilities. Recommendation H.110 is a starting point for network design. The approach currently followed is support for the local TV standard for camera and display equipment. This could be 525 line NTSC on one side and 625 line PAL on the other. Each coder accepts the local standard, and converts it to a common intermediate digital standard (288 lines). The coder then applies bit-reduction processing and forms a signal for transmission. Each decoder processes the received signal, forms a common intermediate digital standard, and then converts this to the local broadcast standard.

Digital transmission channel compatibility also requires changes due to the difference in rates in the digital transmission hierarchy, and in techniques used for framing and synchronization. North America uses 1.544 Mb/s and 44.732 Mb/s rates, while Europe uses 2.048 Mb/s and 32 Mb/s rates. When two systems of differing rates are to be connected, the lower rate is adopted by both sides.

The compatibility question is important in the long term evolution of teleconference communications. The immediate need for communications should not ignore the need for compatibility with other equipment. As the world market continues to evolve, international compatibility with equipment and transmission facilities becomes increasingly more important. The primary purpose of Recommendation H.261 is to help define this compatibility the same way that has been done with facsimile. A number of manufacturers are participating in this standard (which is still evolving), and often offer two versions of operating software. One supports proprietary coding techniques, the other supports H.261 when compatibility is needed. Most suppliers claim then their proprietary technique is superior, but recognize the need to be able to work with equipment from other manufacturers or with signals from another country.

2.2.4 Multipoint Teleconferences

Two point teleconferences are straightforward: each group sees the video from the other group. Multipoint conferences require additional functions for signal distribution, and conference control. Current prices for multipoint control that bridges audio and switches video are near $100 K. This price is certain to be greatly reduced as the demand for multipoint service increases.

In a two way conference, each group sees a display of the other group. As additional parties are added, either additional displays are needed, or video from one or two locations is distributed to all other sites. Decisions for which video is to be displayed at each site become complex. In general, no site should view their own video; it is a waste of signal, and many people feel uncomfortable when watching themselves.

Audio signals from sites participating in a videoconference are bridged. The presence of room echo may limit the number of sites that can be added. Echo cancellation (specially designed for rooms) and push to talk operation are probably both needed.

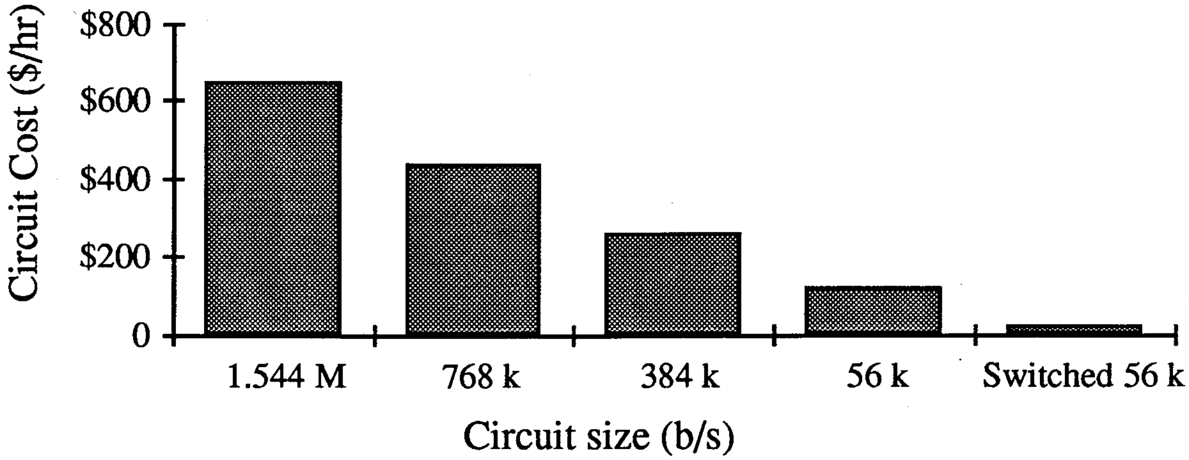

Figure 2–4: Cost of Digital Transmission (1990 $)

2.3 Digital Video Transmission Services

Digital video services are transmission services suitable for videoconference use. Some companies offer complete end-to-end service in public facilities (participants to the a public meeting room), and others simply offer the transmission facilities. Today, most transmission services are provided by satellite or fiber optics.

2.3.1 Sprint Meeting Channel

Sprint Meeting Channel was originally developed by Isacomm of Atlanta, Georgia in the early 1980's using Ku-band satellites. The service, now owned by Sprint, has been moved to Sprint's fiber optic network, includes interfaces to other networks, and retains compatibility with satellite transmission. The service connects rooms owned and operated by Sprint with other public and privately owned rooms. In 1990 the Sprint Meeting Channel comprised 850 rooms in 29 countries: 60 of these are public rooms in the United States, 251 are public rooms in foreign countries, and 539 are private rooms

Sprint Meeting Channel is connected over US Sprint's fiber optic network. Full color and interactive video are transmitted at rates up to 1.544 Mb/s, in increments of 56 kb/s or 64 kb/s; 768 kb/s is standard. Digital cross connect switches are installed at most meeting rooms for access to the digital network.

Sprint Meeting Channel offers two multipoint videoconferencing services: fully interactive multipoint conferencing and basic service. Fully interactive multipoint service uses a voice-activated switch to deliver interactive voice and video to all connected sites. When participants at one location speak, the video circuits at all other sites switches to the site. A short delay reduces extraneous switching.

Basic service includes a "master" and "primary" site, and optionally "secondary" sites. Master and primary sites see each other. The secondary site sees only the master. Interactive audio is provided to all sites through an audio bridge.

Most domestic Meeting Channel rooms use Compression Labs Rembrandt 56 or Rembrandt II/06 codecs.

2.3.2 AT&T

AT&T originally sparked imaginations in 1964 in the teleconference market with PicturePhone, a visual telephone system. Although the system received some interest, the unit was never successfully marketed. AT&T's next entry was the PicturePhone meeting service, a small number of private rooms that was discontinued in 1985 used the NEC Netec 6/3 codec. AT&T offers several services under the Accunet Business Video service, including Accunet 1.5, Accunet 45, and Accunet Reserved Digital Service (ARDS). Accunet Switched Digital Services, Software Defined Network Service, and AT&T Skynet Services also support videoconferencing. AT&T provides portable dishes for customers wishing to use Skynet Digital or Skynet Clearlink for customers without their own facilities.

2.3.3 Contel ASC/GTE Spacenet

Contel ASC was a videoconferencing pioneer and dominates the satellite-based teleconferencing field. Contel provides turn-key videoconferencing service connecting two locations. Contel ASC offers two services: interactive video operating at data rates from 112 kb/s to 768 kb/s, and business television using analog broadcast service using studio quality video and two-way audio.

Interactive video service uses either custom rooms or roll-about carts. Contel has announced an alliance with PictureTel, making PictureTel's C-3000 codec as part of the standard videoconferencing package, but also supports the CLI Rembrandt II/06.

Contel ASC's Channel Management Service (CMS) provides multipoint network control. With CMS, any two sites in the network can participate in an interactive conference. Other sites can monitor the active sites, and can have full audio interaction. The two-way video channel can be switched to any other location allowing them to participate visually as well.

GTE Spacenet markets Ku band services from 56 kb/s to 1.544 kb/s. The metered service charges only for transmission time.

2.3.4 Hughes Network Systems

Hughes Network Systems InTELEconference provides video services through their Personal Earth Station VSAT line. InTELEconference supports broadcast, two-way interactive, and multipoint conferences using 256 kb/s or 384 kb/s TDM video links

2.3.5 COMSAT

COMSAT Video Enterprises offers business television services to conference rooms with multipoint return audio in their video distribution network.

2.3.6 Private Satellite Network, Inc.

PSN systems provide point-to-multipoint analog broadcast video in conjunction with two way audio. Participants can view the presentation on television sets, monitors, or large projection screens, and can call in questions that are heard and answered live over the network. Signals broadcast by PSN can be encrypted using the B-MAC encoding system. PSN entered the market by providing permanent corporate networks. PSN provided design, engineering, installation and maintenance. PSN expanded this base by moving into videoconferencing services, and spun off several programming networks including the Continuing Legal Education Satellite Network and the Institutional Research network.

2.3.7 VideoStar Communications, Inc.

VideoStar derives substantial revenue from the major special event service.

2.4 Conference Room Facilities

Conference room facilities may be dedicated rooms equipped with specially designed furniture, lighting, wall treatments, built-in microphones and speakers, video cameras, monitors, document scanner and display, and control equipment. Other rooms have shared uses. A portable unit is moved into the room shortly before a videoconference session. These rooms may also have special treatment, but not as extensive as the first type. The conference room could also be an office, or can be workstation based and is often used by small groups or individuals. Room equipment may be provided either directly by the codec manufacturer, or by an integrator who provides facilities specifically needed by a customer.

2.4.1 CLI Gallery Series

The Gallery 125 and 225 systems are intended for groups of 1 to 6 people. The Gallery 135 and 235 systems support larger groups. Options include room echo cancellers, switchable microphone control, and full-duplex synchronous sound.

Gallery 125:	Single 25 inch monitor
Gallery 135:	Single 35 inch monitor
Gallery 225:	Two 25 inch monitors
Gallery 235:	Two 35 inch monitors

The Gallery control system supports either prepositioned cameras or a main camera that can be manually panned, tilted, zoomed, or refocussed with a single button. A graphics camera conforming to NTSC standards is an option.

2.4.2 PictureTel Corporation

The V-3100 is a roll-about videoconferencing system incorporating the V-3000 codec. This features a remote control camera, a 25 inch monitor, a full-duplex audio system. An Echo Erase option reduces the audio room echo. An audio privacy switch allows room audio to be disconnected for private conversations during a videoconference. The windowing option allows a reduced image to be displayed in the lower right hand corner of the monitor. This can be used to preview outgoing video, or to display graphics and the remote site simultaneously. An auto preview feature switches the room monitor to the camera while the position is being adjusted.

Far-end control permits users to take control of a unit in a remote room, moving the camera and switching video sources.

The V-3325 system is a dedicated conference room system including two 35 inch monitors; CCD camera with remote pan, tilt, and zoom; a C-3000 codec, and a document camera.

The M-7000 multipoint bridge and control system allows two-way interactive audio and video among multiple sites. The basic system support 3 sites; it can be upgraded to support up to 6 sites in a public network, or 16 sites in a private network. The M-7000 support graphics and full motion video over private networks, switched 56 kb/s networks, and ISDN networks. All calls must be dialed from the hub to prevent unauthorized access.

Conferences can be director controlled or voice-switched. In director controlled conferences, one person determines what is seen and heard. With voice control, the system automatically displays the person who is speaking. The person speaking sees either the director or the last speaker.

The M-7000 director console is a PC-based system that users can install together with the hub, or can connect to the hub remotely via a dial-up line.

2.4.3 NEC 500

The NEC System 500 is a roll-about unit and is modular in design. The system includes a one chip CCD camera that can be upgraded to a three chip camera; a 30 inch monitor; a VisuaLink 1000 or VisuaLink 3000 codec; standard microphone and speaker; and an optional AEC-400 or AEC-700 echo canceller. Other options include a hand-held remote control device with pan and tilt capability for the camera.

2.4.4 Vidicom

Vidicom, a division of L. D. Bevan Company, Inc., provides portable video conference equipment in a roll-about cabinet. This includes a switchable camera, 26 inch monitor; switchable camera with pan, tilt and zoom; two microphones and audio mixer; echo canceler; bridge; amplifier; speakers, and controller. The unit includes a user's choice of video codec. Model number include the 3300 Europa, 3351 and 3352. Optional features include additional cameras, microphones, graphics stand, and wireless control.

2.4.5 Video TeleCom Corporation

Conference System 320 includes two 20 inch monitors, two microphones, CCD main camera, document stand, room controller.

Conference System 525 includes two 25 inch monitors; two microphones; three cameras; document stand; room control; remote pan; tilt, zoom and focus; graphics with annotation.

2.4.6 Videoconferencing Systems, Inc.

Videoconferencing Systems, Inc. supplies remote controlled motion and graphics cameras. Units feature single-chip cameras that can be controlled from a remote location. Five models are offered: Associate (roll-about), ProjectMaster (roll-about), Spectra (in-wall), Omega (roll-about), and Spartan (roll-about).

2.4.7 Eyetel Interactive Dynamic Display System

Interactive Dynamic Display System (IDDS) interfaces with any codec. The system offers 2 video monitors, frame grab capabilities, on-screen drawings.

2.5 Videoconference Codecs

Videoconference codecs provide visual communications capability. They accept standard signals from a camera, and deliver a standard signal to a monitor, but use a number of techniques to reduce the transmission bit rate. "Broadcast video" can be delivered by transmission paths supporting D3 rate (32 Mb/s to 44.7 Mb/s) codecs. These codecs achieve 2:1 or 3:1 reductions in bit rate with little or no loss in quality using digital coding techniques.

Many videoconference codecs operate at rates from 56 kb/s to 1.544 Mb/s. This requires reduction factors of 16 to 500. The amount of information to transmit is proportional to the square of the spatial resolution. Reducing the horizontal resolution by half can provide a 4:1 reduction in bit rate. Decreasing the temporal sampling rate to 15 or 10 frames per second further reduces the bit rate by a rate of 8 or 12. The remaining reduction is achieved by more advanced coding, by further restrictions on spatial and temporal resolution, and restrictions on the ability to display rapid motion.

2.5.1 British Telecom VC 2100

The British Telecom VC 2100 codec complies fully with CCITT Recommendation H.261. The system supports both Common Intermediate Format (CIF) and Quarter CIF (QCIF), providing compatibility with systems supporting either format. At CIF, video resolution is 352 pixels horizontal by 288 lines vertical. Video compression uses H.261 inter- and intra-frame coding techniques together with discrete cosine transforms.

Data rates range from 64 kb/s to 2.048 Mb/s in 64 kb/s increments. Video interface includes NTSC, PAL, and RGB.

The unit can be configured through either local controls or an RS-232 interface. Two expansion ports allow access to the unit from two terminals, or allow control of multiple codecs from a single terminal. Additional ports support facsimile, electronic whiteboards or graphic tablets or other data communications applications.

An optional adapter card allows access to dial-up ISDN facilities, supporting transmission rates from 64 kb/s to 128 kb/s with user-selectable video and audio bit rates (48 kb/s to 112 kb/s video, and 16 kb/s to 56 kb/s audio).

2.5.2 PictureTel C-3000 Codec

PictureTel originally used Motion Compensated Transform (MCT) compression technology. The codec consists of a signal processing module and a software module. In 1988, the software module was replaced, and Hierarchical Vector Quantization (HVQ) coding technique replaced the MCT. In 1990, an upgrade to HVQ coding was released. PictureTel claims a 70% increase in image quality at the same rate.

The basic Link-64 codec operates at bit rates from 64 kb/s to 384 kb/s with a resolution of 256 x 240. At 112 kb/s, the codec operates at 10 fps. Audio is an integrated 8 kb/s to 64 kb/s codec. Interface includes T1, fractional T1, and satellite.

PictureTel also released an initial version of CCITT H.261 video compression standard. The Link-64E support 352 x 288 line resolution. Link 2.0 increases to maximum transmission rate to 2.048 Mb/s at the 352 x 288 line resolution.

2.5.3 CLI Rembrandt

The Rembrandt system includes CLI's DXC codec operating at speeds from 384 kb/s to 3.136 Mb/s. The system can operate at increments of 56 kb/s or 64 kb/s. Resolution is 180,000 pixels per screen, making it suitable for medium to large groups.

Options include:

- NTSC, PAL, RGB interface (for graphics).
- 480 x 368 resolution
- Up to 8 motion or graphics sources.
- Audio
- DES encryption.

The codec operates at 1.544 Mb/s and 2.048 Mb/s rates, and is compatible with satellite, fiber, microwave, or cable transmission.

Data and graphics share the video and audio channel. Still frame graphics includes a cursor option. Simulvision, a special effects option, can combine two full-motion images for a split-screen display.

2.5.4 CLI Rembrandt II/06

The Rembrandt II is a low bit rate codec that is also marketed by AT&T. The codec operates at speeds from 56 kb/s to 384 kb/s using CLI's new DCT-based Cosine Transform eXtended (CTX) mode.

Options include:

- Motion resolution: 240 lines x 256 pixels for NTSC, 288 x 256 for PAL
- Graphics resolution: 480 x 512 for NTSC, and 576 x 512 for PAL.
- At 56 kb/s to 112 kb/s, 10 frames/second for NTSC and 8.33 fps for PAL.

- At 128 kb/s to 384 kb/s, 15 fps for NTSC and 12.5 fps for PAL.
- Audio bandwidth options include 8 kb/s (VAPC), 16 kb/s (ATC), and 32 kb/s or 64 kb/s (ADPCM).

The Rembrandt II is compatible with the Rembrandt 56 codec.

The Multipoint Control Unit (MCU) operates with any unit allowing either voice- or manual-switched multipoint videoconferencing. Two MCUs can be configured to support up to 14 sites in as many as 5 simultaneous conferences. The MCU supports the codec's still frame and motion graphics capabilities, DES encryption, and switched digital transmission.

2.5.5 GPT System 261

GPT markets the British Telecom VC 2100 Codec as the System 261 within the United States.

2.5.6 NEC VisuaLink 1000

NEC started developing codecs in 1971 and produced the NETEC 6/3 codec that was accepted for use in the AT&T PicturePhone Meeting Service. This led to the development of the NETEC-X1, the first coder operating at T1 rates. NEC VisuaLink codecs are based on the NETEC line.

The NEC VisuaLink 1000 uses motion-compensated interframe and transform coding with variable word length coding providing transmission rates from 56 kb/s to 384 kb/s. The compression technique algorithm can be upgraded in the field by issuing a new software release.

A number of attractive features are included. A multifunction, wireless hand held remote unit allows an operator to operate equipment without interrupting the teleconference. Data rates are user selectable from 56 kb/s to 384 kb/s using the RS-449 interface. With the V.35 interface, rates are 56 kb/s or 64 kb/s. The RS-449X2 supports 112 kb/s or 128 kb/s.

Video input and output is either NTSC or PAL. One still video input port and three motion-video input ports are provided. Image resolution is 288 lines x 176 pixels Audio options include 3.4 kHz using microwave pulse generator (MPG) coding or 7 kHz audio using 56 kb/s ADPCM (adaptive differential pulse code modulation) coding.

2.5.7 NEC Visualink 3000

The NEC VisuaLink 3000 codec includes universal format adapters that provide signal conversion, allowing this codec to be used with the H-261 international standard. Twenty five user rates from 384 kb/s to 2.048 Mb/s are standard.

Like the VisuaLink 1000, the codec provides motion compensated interframe and transform coding with variable word length coding.

Video encoding is composite color with sampling rates of 13.5 MHz, 8 bits; and picture resolution of 288 lines x 352 pixels for both motion video and graphics. A/D accuracy is 8 bits, and D/A accuracy is 9 bits.

The 7 kHz audio uses 56 kb/s ADPCM (adaptive differential pulse code modulation) coding.

Other standard features are similar to the VisuaLink 1000 codec.

2.5.8 NEC Broadcaster and HO DPCM 45BIII

The NEC America Broadcaster 45 is a D3 interface (44.732 Mb/s) codec providing "broadcast" quality digital transmission for the television industry. One video and up to four 15 kHz audio signals can be transmitted over a standard DS3 circuit.

The signal is first converted to a 90 Mb/s PCM signal that is then reduced to 45 Mb/s using predictive coding. The unit features higher order differential pulse code modulation (HO-DPCM) that codes the signal using four different coding algorithms, then chooses the one with the lowest rate.

The HO-DPCM 45BIII codec transmits a color or monochrome TV signal and two 10 kHz audio signals. It uses the B3ZS code format with DS3 framing. A/D accuracy is 8 bits. The system is advertised as providing "commercial" quality video at T3 rates.

2.5.9 Concept Communications Image 30

This product has 256 x 200 resolution with 512 x 400 for graphics.

2.5.10 Video TeleCom, Inc.

Cameras included in the Conference system 320 and Conference System 525 use DCT transform coding with a video resolution of 256 x 240 resolution. A PC-AT computer with hard disk drive is included in the codec. [Other details not available at this time.]

2.5.11 Eyetel

Further investigation needed for Eyetel codecs. Offerings include:Vistacom fixed rate codecs 56/64 kb/s, 112/128 kb/s, 256 kb/s with resolution of 256 x 240 lines at 15 fps. Compression uses predictive coding with block coding. Vistacom variable rate codecs from 56 kb/s to 384 kb/s. Vistacom Videophone 384 kb/s is H.261 compatible, and includes ISDN interface. Vistacom Videophone 56/64 is a desk top unit.

2.5.12 PictureTel & Intel Workstation Based Video Conference Development

PictureTel and Intel announced an agreement to jointly develop interactive digital video processing technology expected to yield workstation-based videoconferencing and multimedia products by 1992. The target is high-quality videoconferencing and multimedia capabilities on a single microcomputer expansion board. The board is to add standards-based motion video communications capability to Intel's Digital Video Interactive (DVI) multimedia technology. The target capability is $3,000 per workstation. PictureTel's contribution is video compression expertise. The unit is to be based on CCITT H.261 standards, e. g. P x 64 implementation. [Reference 3.]

Multimedia currently integrates computer graphics and text with digitized audio, still images, and motion video, usually in interactive networked applications. DVI is currently available only for 80386 based products: IBM PC and PS/2-compatible models.

Intel's implementation is based on the i750 family of processors consisting of a two-board set for application development, an a single board for DVI playback. The two board development platform performs audio and video digitization, compression and decompression, image manipulation, special effects creation, and playback.

2.5.13 Other Workstation Developments

Several workstation products now allow a real-time video window to be displayed on the workstation. A number of workstations have full color displays with resolutions of approximately 1200 x 900 lines. A quarter image picture of 176 x 144 therefore occupies only about 2% of the area, and a 352 x 288 line image occupies about 9% of the workstation area. Interest in this display technology is initially for multimedia displays; the window can display video from a video laser disk or VCR in response user queries. This computer and display technology can be combined with videoconference codecs to form the basis for person to person videoconferences. The PictureTel/Intel development can be an integral part of this system.

2.6 Still Image Transmission

Still image transmission sometimes called freeze-frame, slow-scan, or captured video, capture a single video image and transmit over phone lines at rates from 2.4 kb/s to 64 kb/s. Images are motionless and only can be sent one at a time. Peripheral devices allow storage, printing, or annotation using devices such as graphics tablets. Advantages for some applications are higher resolution than low-rate motion video, small size, and lower cost.

Visual communications using still images is expected to grow exponentially. Areas for expected growth include radiology, law enforcement, stress analysis, and remote monitoring. The Immigration and Naturalization Service, for example, often needs to check the validity of passports or other identification. Stores may check ID and signatures with credit companies.

2.6.1 Colorado Video

Colorado Video, a pioneer, offers still frame equipment, frame stores, and computer interfaces. The Model 286 transceiver is a compact system for integration into full systems. The unit is compatible with images from cameras, VCRs and video laser disks. Model 290 and 209C (color) transceivers convert still images into slow-scan television signals for analog transmission over voice grade lines. Transmission speed depends on resolution.

2.6.2 Kodak SV9600 Series

The Kodak SV9600 series is RGB and NTSC compatible. Applications include news stills and medical imaging. Edicon, a Kodak company that manufactures image database systems markets the Kodak SV9610 as an optional feature.

Transmission is at a nominal rate of 9.6 kb/s, but can be reduced to 2.4 kb/s if line quality is poor. Signals are RGB and NTSC compatible. The unit can be integrated with fixed videoconferencing installations, and connects with thermal video printers for hard copy.

2.6.3 PhotoPhone

Image Data Corporation was spun off from Datapoint Corporation in 1983, just before divestiture. Image Data concentrates on high quality grayscale still imaging. Image Data markets the Photophone, a 592 x 440 line resolution and 256 shades of gray (8 bits). Transmission of the image uses ADPCM (adaptive differential pulse code modulation). Interface is RS-232 or ISDN basic interface.

A color version, the Image Terminal, is VT-100 compatible, supports grayscale video display, video display, PC display software.

The ImagePackage software allows image transmission over electronic mail systems and its TIFF conversion package converts PhotoPhone images into tagged image file format files for desktop publishing. Multiview allows a stand alone or PC-based teleradiology system to display multiple images in a single screen.

2.6.4 Interand

Interand is best known for the Telestrator graphics system that supports real time annotation of still o motion video images. Telestrator has gained recognition as CBS Sports' "Chalkboard" and is frequently used for television news shows' weather reporting. The Imagephone is an integrated desktop grayscale system allowing up to eight sites to interact simultaneously. Control uses mouse and touch panel. The System 900 and 950 are color systems based on the Telestrator. The 900 uses a mouse; the 950 a graphics tablet.

2.6.5 Optel Communications

The current version, the Telewriter 3 PC, is PC based. Uses include distance education, design, advertising and medical imaging.

2.6.6 Videophone

A PC-based portable desktop unit with a single-person switched camera. Resolution of 512 x 512 and support for graphics tablet and modem are advertised.

2.7 Predictions for Future Equipment and Standards

Videoconference codecs will continue to gradually improve in quality and prices will continue to decline. The biggest change is expected to be in lower prices due in large part to VLSI and high speed digital signal processing chip development. ISDN and B-ISDN will also bring changes due to increased customer access to higher rate digital channels.

Three videoconference quality levels can be expected to evolve:

56 kb/s to 128 kb/s. The basic ISDN service will make 2B (128 kb/s) service widely available. Videoconferences involving a few people will be able to use this service. This service will support reduced resolution motion video, and higher resolution still and graphics. Expect that new higher resolution displays will display several channels in separate windows.

n x 384 kb/s. This will continue to be the primary service for small groups (6 to 10 people at each site). The increased bit rate allows higher resolution motion video and improved audio channel bandwidth. Codec manufacturers will eventually cross license improved coding to allow these to be incorporated into the standard.

Business Television. Current DBS development work will produce codecs with higher performance than currently available. Spatial and temporal resolution will approach broadcast quality at rates between 2.048 Mb/s and 8 Mb/s.

The large number of different standards currently found will disappear; customers will require adherence to widely accepted standards to increase the number of other locations that can be reached with visual communications.

References

[1] Datapro Reports on Communication Alternatives, CA80-020-101, "An Overview of Business Television", McGraw-Hill.

[2] CCITT Volume III - Fascicle II.6, "Line Transmission of Non-Telephone Signals", Geneva 1989.

[3] DataPro, Communications Alternatives, "Technology Trends", August 1990.

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Chapter 3

Estimate of Traffic

3.1 Traffic Model

As indicated in the recent study, "Applications of Satellite Technology to B-ISDN Networks" [NASA, Lewis Research Center Contract No. NAS3-25092], it was envisioned that the United States domestic telecommunications infrastructure in the year 2010 will encompass several large public switched networks, a large number of private service-specific networks (such as the Inter-hospital network, the High School network, the supercomputer network, etc.), and many centralized information centers (Library of the Congress, Company Headquarters, major Medical Research Centers, etc.). All these networks are accessible to the general public and are fully B-ISDN compatible. For most of these terrestrial-based networks, optical fiber is the dominant technology.

It is anticipated that the use of satellite-based networks could offer three distinct applications:

i. to bridge private service-specific networks and/or information centers. Here, each of these networks can be looked upon as a gateway through which the end users can access the satellite;

ii. to enhance the service quality of and/or to extend the service coverage for the public switched networks; and

iii. to provide network diversity and backup.

The applications of integrated video over satellites can be treated as a subset of the bigger satellite B-ISDN market having some specific traffic requirements as summarized below:

- User friendliness
- Affordable, competitive cost
- Provision of "service on demand" features
- VSAT size terminal (1.2 m to 3 m antennas)
- Wide range of information rates from 64 kb/s to 6 Mb/s
- Flexible quality of service depending on applications

In particular, this Study focused on four (4) integrated video applications:

Tele-Medicine. Remote diagnosis and analysis for second opinions, teaching and other purposes, transfer of medical records and images, remote database searches, remote operation room assistance, etc. Data rates will range from 64 kb/s to 6 Mb/s.

Virtual Offices. Inter-office meetings, client conferences, employee training, resolving program and production problems.

CAD/CAM. Real time changes to manufacturing process to match instantaneous needs of unique customer requirements. Allows limited custom product variations to come off a production line. Data rates will range from 128 kb/s to 6 Mb/s.

Video Retrieval. Employee training, production method reminders, videos of machine setups, application videos. Data rates will range from 128 kb/s to 2 Mb/s.

3.2 Capacity Requirements

It is estimated that the integrated video traffic covering the above four applications will amount to a total of 1,500 T1 lines or to an aggregated information bit rate of 2.3 Gb/s. This will include a 1.4 Gb/s (900 T1 lines) network covering the application requirements for both Virtual Offices and CAD/CAM. Similarly, a 900 Mb/s

(600 T1 lines) network will be needed for telemedicine which, in turn, will time share with the use of video retrieval.

A heuristic approach similar to the one employed in the B-ISDN Study was used to establish a first-order estimate of the demand for integrated video services as follows:

- By the year 2010 there will be 2.16 million United States corporations whose yearly sales exceed $5 M. The assumption is that 1% of these corporations will require satellite delivered integrated video services at T1 rate for 1/2 hour per day. This results in a total of 900 T1 lines to be time shared by virtual Offices and CAD/CAM over a 12-hour day (i. e., 21,600 x 1/2 x 1/12 = 900).

- Similarly, there will be 1.2 million doctors in the United States by the year 2010. Out of this total there will be 24,000 radiologists and 640,000 specialists. The forecast assumes that 1% of the 664,000 doctors will use an average of one hour T1 per day. This results in 600 T1 lines to be time shared by telemedicine and video retrieval over a 12-hour day.

Chapter 4

System Architecture

This chapter contains a detailed satellite architecture for the provision of integrated video services. This architecture supports video services with user bit rates ranging from 64 kb/s to 6 Mb/s, with a maximum network capacity of 3 Gb/s. Services requiring higher bandwidth, such as HDTV, may be carried on satellites with broadband capabilities. This chapter is organized as follows:

There ia a list of references at the end of the chapter.

4.1 Introduction

Figure 4-1 illustrates the basic concept for the integrated video network, where the satellite provides full mesh connectivity to users through the use of small spot beams and on-board processing. Typical applications are illustrated, including videoconferencing and point-to-multipoint video telecasts. The architecture provides for many similar network configurations simultaneously.

The network must allow flexible interconnection of user terminals, including point-to-multipoint capabilities. Many of the video services, such as video conferencing and video distribution, rely on point-to-multipoint or even multipoint-to-multipoint connection capabilities. A topology and signaling network to support these connections must be provided by the network architecture.

For integrated video, a full mesh topology is preferred for two main reasons.

i. Video services such as video conferencing are delay sensitive so multiple hops must be avoided.

ii. Traffic concentrations in this network for particular types of traffic (e. g. videoconferencing) will shift frequently, requiring a robust, distributed network with flexible resource allocation.

Although full mesh topology with many spot beams requires a more complicated on-board switch, the extra processing is necessary to adequately provide the network services. Although video telephone and video conference standards are still emerging, a few preliminary conclusions may be drawn that help to shape the design of an efficient architecture.

- In general, video service information rates will most likely be multiples of a base rate of 64 kb/s, up to approximately 6 Mb/s. The provision of these service rates is a key consideration in the network design.

- A flexible network control strategy must be provided to insure efficient and cost-effective use of the network and satellite resources.

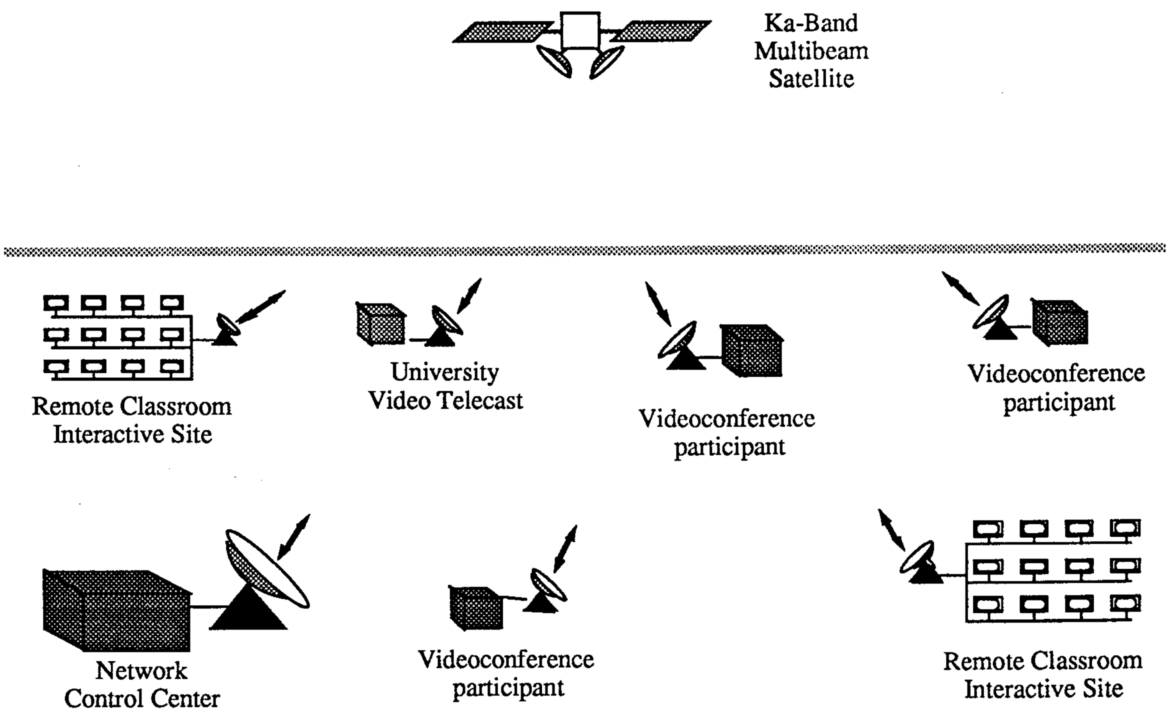

Figure 4–1: Integrated Video Network in which Satellite Provides Full Mesh Connectivity

4.2 Bandwidth Considerations

One of the key considerations in defining the network architecture is bandwidth availability. Ka-band is selected because of the large capacity required by an integrated video network. Current frequency allocations as defined by CCIR are given in [1]. Only portions of the Ka-band not shared by other types of satellite services on a primary basis are considered for use.

Sharing with terrestrial fixed and terrestrial mobile services is not expected to be a problem. Bands that are allocated to fixed satellite services on a primary basis and to mobile satellite services on a secondary basis are also considered readily usable.

Although the Ka-band provides sufficient bandwidth, its use has some disadvantages. Rain fades at these frequencies are large, especially on the uplink, which forces the system to incorporate either large clear-sky margins or uplink power control. Also, at Ka-band frequencies, significant depolarization occurs during rain, so that cross-polarization isolation degrades rapidly. Consequently, cross-polarization is only used to add to other isolation techniques, such as frequency and spatial isolation.

4.2.1 Downlink Bandwidth

Figure 4-2 (top) shows the current downlink frequency allocations in the range from 17.7 to 20.2 GHz. In this range, bandwidth is allocated to be shared among a variety of non-government services, including fixed satellite space-to-earth services. The band from 17.7 to 19.7 GHz is allocated to fixed satellite space-to-earth services on a primary basis, along with terrestrial fixed and mobile services.

However, some portions of this band are reserved for special types of fixed satellite space-to-earth services. Of the total allocation between 17.7 and 19.7 GHz, only the portions from 18.3 to 18.6 GHz and from 18.8 to 19.7 GHz have been considered for use. The band from 19.7 to 20.2 GHz is allocated to fixed satellite space-to-earth services on a primary basis, and to mobile satellite space-to-earth services only on a secondary basis. As a result, 1.7 GHz of bandwidth, including the bands from 18.3 to 18.6 GHz and from 18.8 to 20.2 GHz, is assumed to be available on the downlink.

(After the completion of this work, WARC 1992 changed the 19.7 to 20.2 GHz allocation to sharing with the mobile satellite services on a primary basis. Thus only 1.2 GHz bandwidth is readily available.)

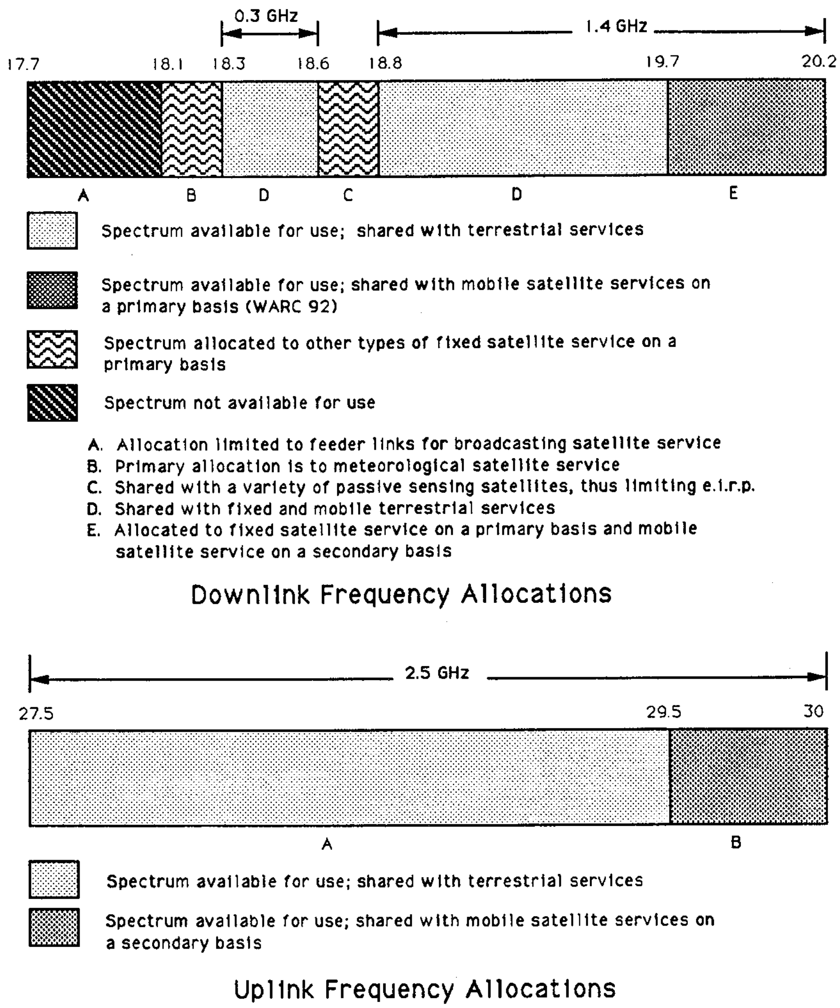

Figure 4–2: Ka-Band Downlink and Uplink Frequency Allocations

4.2.2 Uplink Bandwidth

Figure 4-2 (bottom) shows the current uplink frequency allocations in the range from 27.5 to 30.0 GHz. In this range, bandwidth is allocated to be shared among a variety of non-government services.

The band from 29.5 to 30.0 GHz is allocated to fixed satellite earth-to-space services on a primary basis, and to mobile satellite earth-to-space services only on a secondary basis.

The band from 27.5 to 29.5 GHz is allocated to fixed satellite earth-to-space services on a primary basis, along with fixed and mobile terrestrial services.

As a result, 2.5 GHz of bandwidth, in the band from 27.5 to 30 GHz, is assumed to be available on the uplink. This allocation was not affected by WARC 1992.

4.3 Transponder Access and Transmission Rates

A number of alternatives exist for providing satellite transponder access.

FDMA (frequency division multiple access) systems may use SCPC and SCPC/DAMA methods. For high capacity utilization, this requires multiple carrier sizes to accommodate the different user service rates, which makes on-board demodulation more complex and resource allocation more difficult.

CDMA (code division multiple access) has shown promise in the area of low-cost VSAT networks. CDMA is characterized by small antenna sizes and resistance to RF interferences. However, its main drawback is the limited channel bit rate (1.2 kb/s) that is achievable in most networks, which is insufficient for video services.

TDMA. High speed time division multiple access is another option which requires high transmission rates and, consequently, bigger terminals.

MF/TDMA. A more efficient access method for this network is multi-frequency TDMA. MF/TDMA combines the benefits of TDMA in providing a variety of access rates with lower transmission rates per carrier, thereby reducing the terminal size requirement.

Tradeoffs also exist between different transmission rates. An important consideration is that most video services are expected to require a rate of 64 kb/s or a multiple thereof, up to approximately 6 Mb/s. Ideally, it is desirable for a particular earth station to access the satellite network at the particular bit rate that it requires (such as in a SCPC system with flexible carrier rates). Although flexible on-board multicarrier demodulators may be designed to handle carriers of arbitrary bit rates, such designs are prohibitively power consuming. Multi-frequency TDMA offers similar flexibility while also reducing on-board complexity through the use of uniform carriers.

For the integrated video network, two carrier rates, 2 Mb/s and 6 Mb/s, are selected. The frame format within the carriers allows for access at a multiple of 64 kb/s. If an earth station requires the whole bandwidth of a carrier, it may use the carrier exclusively in a TDM mode. Furthermore, an adaptive technique may allow users to drop their carrier rate from 6 Mb/s to 2 Mb/s to combat rain fade.

4.4 Transmission System Design

4.4.1 Antenna Coverage

The selection of an antenna beam coverage pattern is driven by two competing factors:

- Use of many small spot beams is desirable for reducing the required terminal size of earth stations.
- More on-board processing is required to interconnect a larger number of beams.

At one extreme is a single global beam, which requires very large terminals and distributes capacity less efficiently, but which eliminates switching on the satellite. To achieve small earth terminals, a network consisting of many small spot beams may be used, although this raises the complexity of the on-board processor.

Additionally, a hopping beam antenna array is possible. This approach achieves both small spot beams and flexible resource allocation, since dwell times of the hopping beam over certain areas may be adjusted to meet traffic requirements. The main drawbacks of the hopping beam approach include a more complicated antenna array and control algorithm to coordinate the network.

For the integrated video network, small earth terminals are desired, the on-board processor complexity must be kept as low as possible, and the available bandwidth is limited. A coverage pattern that meets all of these requirements is shown in Figure 4-3. Twenty-eight fixed spot beams of 0.87° diameter provide continental U. S. (CONUS) coverage for the uplink and downlink; the coverage is symmetric. Isolation is achieved through a frequency reuse factor of 7, so that each beam area, which may have a bandwidth of up to 150 MHz, has a different frequency than its six neighboring beam areas. Therefore, a total system bandwidth of 1.1 GHz is used. This particular beam pattern is chosen to maximize antenna gain while also keeping the switching and hardware requirements on the satellite at a manageable level. As a result of using this size spot beams, terminal sizes as small as 1.2 m can be used.

4.4.2 Modulation and Coding

A modulation and coding scheme must be employed to fit the proposed system capacity of 3 Gb/s within an available downlink bandwidth of 1.7 GHz with reasonable power efficiency. Because of implementation considerations and the nonlinear amplitude distortion encountered on the satellite channel, PSK modulation is selected to provide for simpler receivers. Within the set of PSK modulation, QPSK is selected for both links. QPSK is twice as bandwidth efficient with only a minor implementation loss compared to BPSK. Higher order modulation (e.g. octal-PSK) is more complex for terminals and on-board demodulators than BPSK, and the extra bandwidth efficiency over QPSK is not necessary for this architecture.

In particular, differentially encoded QPSK is used on the uplink. The differential coding, a rotationally invariant FEC code which is insensitive to 4-fold phase ambiguity, is used outside of the FEC/modulator ar-

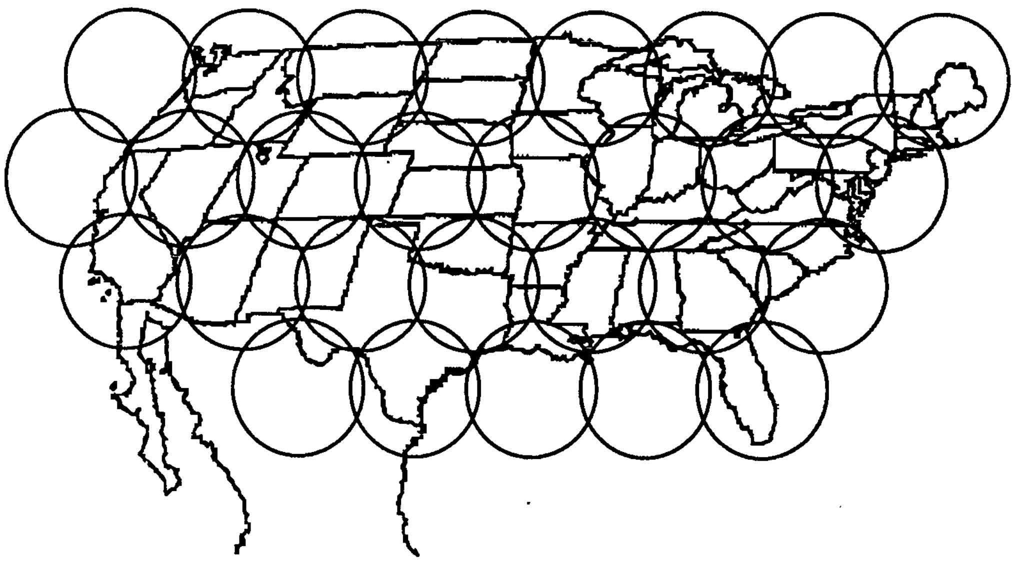

Figure 4–3: 28 Fixed Spot Beams of 0.87° Diameter Cover CONUS for Both Uplinks and Downlinks

rangement to provide carrier phase synchronization on the uplink. Such a setup is not necessary for demodulation on the downlink since the TDM streams are from a single source. The differentially encoded QPSK degrades the bit error performance by a factor of two, since errors occurring on a differentially encoded data stream tend to occur in pairs.

A forward error correcting code is selected in combination with the QPSK modulation to lower the channel error rate. A rate 1/2 convolutional code (16 state code with a gain of 5.4 dB) is selected for this network to provide improved bit error performance. Because sufficient bandwidth (due to modulation techniques) is available, a low rate code is chosen to minimize the necessary power requirements and complexity on-board the satellite. It is anticipated that coding gain advances will allow for even better performance.

4.4.3 Rain Fade Mitigation Strategies

There are two means whereby rain fade attenuation may be compensated:

i. Allow for enough clear-sky margin to sufficiently cover the rain attenuation to an acceptable level.

ii. Adaptively change transmission parameters in the case of rain.

At Ka-band, uplink rain attenuation can be as large as 20 dB, but relatively high availability (99.5%) may be maintained with a much smaller fade margin (6 dB) in most parts of the United States.

Adaptive techniques, such as power control, adaptive FEC, or transmission rate reduction, are preferred when availability must be kept very high, but the increased complexity may not be desired in the case where availability is less critical. Greater availability may be achieved in heavy rainfall regions by using any of these adaptive techniques on the uplink or by increasing the terminal size.

4.4.4 Transmission Summary

A summary of the key transmission parameters and architecture characteristics is given in Table 4-1. To allow many users access to the network at a low bit rate, multi-frequency TDMA and TDM are used on the uplink and downlink respectively.

As described in ¶4.5, each uplink beam is dynamically allocated information rates of between 36 Mb/s and 108 Mb/s, in multiples of 36 Mb/s, based on capacity requirements. On the uplink, these 36 Mb/s blocks either consist of eighteen 2 Mb/s carriers or six 6 Mb/s carriers. Earth stations may access either a 2 Mb/s carrier or a 6 Mb/s carrier, depending on availability in a particular beam. On the downlink, two 54 Mb/s TDM carriers are used in each beam. The maximum information rate available in any uplink or downlink beam is 108 Mb/s. The frame structures for both of these formats are described in ¶4.8.

Table 4–1: System Parameters for Integrated Video System Design

System Parameters	Uplink	Downlink
Frequency	30 GHz	20 GHz
Number of beams	28 fixed	28 fixed
Access method	TDMA	TDM
Modulation	D-QPSK	QPSK
FEC convolutional coding	R=1/2	R=1/2
Information bit rate per beam	36, 72, or 108 Mb/s	54 or 108 Mb/s
Transmission bit rate per beam	72, 144, or 216 Mb/s	108 or 216 Mb/s
Bandwidth allocation per beam	150 Mb/s	150 Mb/s
Frequency reuse pattern for isolation	7	7
Total system bandwidth required	1.1 GHz	1.1 GHz
Carrier bit rate (information)	2 or 6 Mb/s	54 Mb/s
Capacity of MCDs	36 Mb/s	–
Number of MCDs	84	–
Number of carriers/beam (maximum)	30	2
Total number of available carriers	840	56
Beam capacity (maximum info rate)	108 Mb/s	108 Mb/s
Satellite capacity (1 satellite)	2.6 Gb/s	2.6 Gb/s
Satellite transmit power per 54 Mb/s channel	–	13 W
Total satellite transmit power (49 channels)	–	637 W
Earth station diameter	1.2, 1.8, 3 m	–
Earth station transmit power	4 – 12 W	–

In this architecture, sufficient link performance is available for terminals ranging in size from 1.2 to 3 m and in power from 4 to 12 W. Figure 4-4 illustrates the tradeoffs between earth station size and annual average availability in two U. S. rain regions (D and E). Because the satellite transmit power is limited to approximately 700 W for the selected bus design, this figure is determined based on the downlink margins.

Figure 4-4 shows that terminals can be kept below 2 m size if availability requirements are not strict, but that to achieve availability greater than 99.5% availability in these locations, terminal sizes must be increased. The selection of terminal size and amplifier power will be based on geographic location and desired channel availability.

4.5 On-Board Baseband Processor

The design considerations described in the previous sections identified the requirement for an on-board baseband switch to interconnect the uplink and downlink coverage regions. This section describes one possible implementation of an on-board baseband processor for the integrated video network. In this section, key components of the payload are described in detail.

The basic functions performed by the on-board processor include the following:

- Demultiplexing and demodulation on uplink carriers,
- Processing of the demodulated data,
- Switching at baseband to the destination ports,
- Processing of the switched data for remodulation, and
- Remodulation on downlink carriers.

The control system of the processor is also responsible for monitoring and controlling the processor subsystems and for processing channel requests. This control system interacts with a network control station in one of the beams.

Figure 4-5 shows the basic configuration of the on-board baseband processor. The block diagram includes

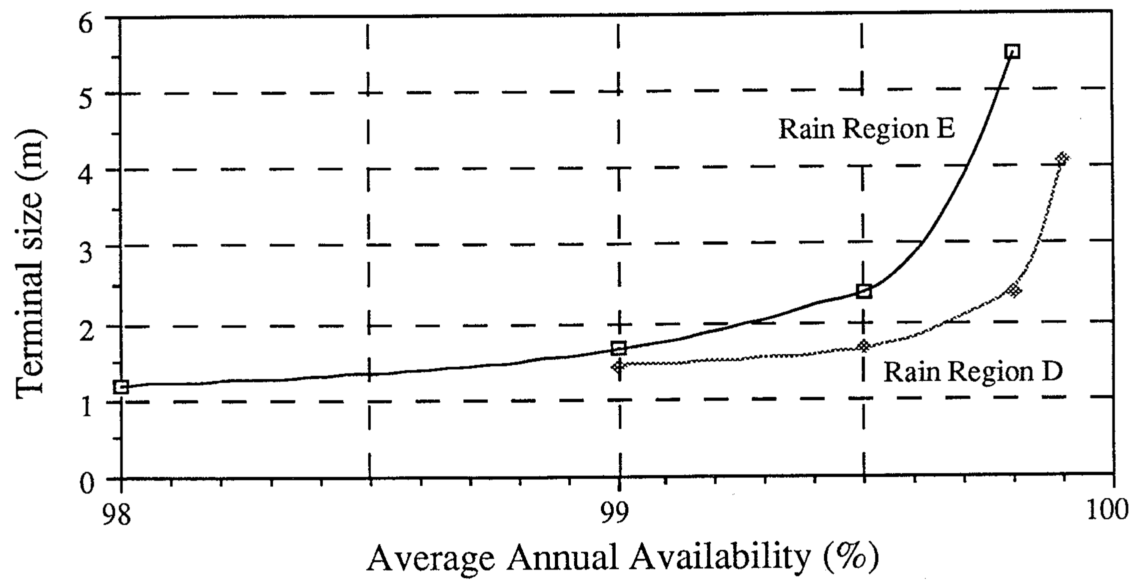

Figure 4–4: Earth Terminal Sizes vs. Availability for Rain Regions D and E

demodulators (shown as MCDs or multicarrier demodulators), input processors, a baseband switch, output processors, modulators, and a on-board network controller. For each uplink and downlink beam there could be a number of these functional blocks which all feed to the baseband processor.

4.5.1 Multicarrier Demodulators

With the use of multi-frequency TDMA, some method must be used to efficiently demodulate multiple carriers. One possible approach is to include separate filters and demodulators for each carrier. For a large number of carriers this approach could result in high payload mass and power requirements. A more efficient approach is to A/D (analog to digital) convert the composite uplink signal and digitally demultiplex and demodulate data from several carriers simultaneously. R&D activities in the area of transmultiplexers or multicarrier demultiplexers and demodulators (MCDs) are currently being conducted by NASA, COMSAT, TRW, Westinghouse, and several other private laboratories [2].

Efficient implementation of digital demultiplexers is a critical issue in the design of on-board processors for multi-carrier satellite systems. The implementation of MCDs on-board satellites is complicated by timing and synchronization issues. Using current technology, MCDs would be prohibitively power-consuming; however, expected technological advances within this decade should drop the power dissipation to workable levels.

There are several methods by which digital data can be demultiplexed by signal processing means. Fast fourier transform [FFT] techniques can accommodate a variety of carrier bit rates. Demultiplexing on a per-channel basis, instead of a block approach, reduces the complexity if the number of carriers is low. If the channel contains uniform carriers, the polyphase approach takes advantage of the use of a uniform filter size to cut the complexity of the FFT approach in half [3].

For the integrated video network, a flexible combination of carrier bit rates was desired initially, based on expected variations in traffic patterns. The FFT approach was considered, based on its ability to handle multiple carrier data rates. The total power dissipated by the MCDs is estimated at approximately 1.1 kW for the FFT approach.

The polyphase approach is chosen to reduce on-board power requirements. This type of MCD, when used with uniform carriers, cuts the complexity (and power dissipation) in half with respect to that of the FFT approach. Consequently, two types of polyphase MCDs are incorporated into the architecture, 28 MCDs for 2 Mb/s carriers and 56 MCDs for 6 Mb/s carriers, for a total of 84 MCDs. Up to three MCDs may be flexibly assigned to any uplink beam.

MCD complexity is a function of the number of carriers and the total bandwidth. The complexity increases linearly with bandwidth and logarithmically with the number of carriers. Therefore, contrary to intuition, it

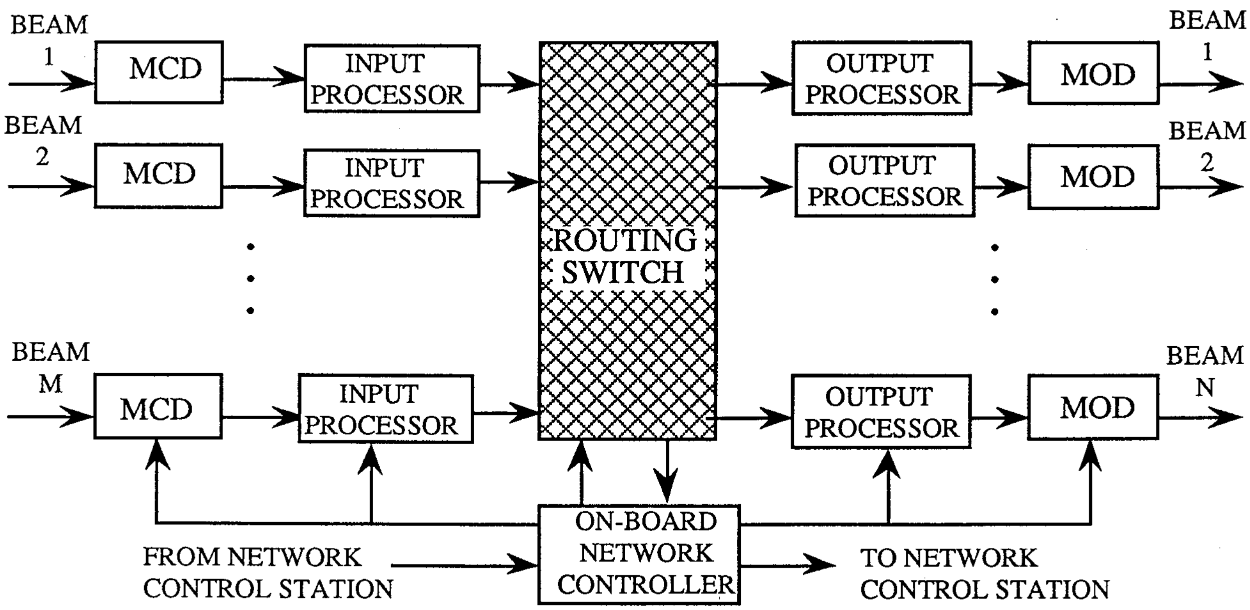

Figure 4–5: Basic Configuration of On-Board Baseband Processor

is not advantageous to consolidate smaller MCDs into larger MCDs, because of the logarithmic scaling based on the number of carriers. For this reason, up to three separate MCDs are used in each of the 28 beams, instead of one MCD with a large capacity.

4.5.2 Alternative Baseband Switch Designs

Paramount considerations for a satellite switch architecture include the following:

- Processing capacity,
- Mass and power consumption,
- Flexibility,
- Congestion control,
- Hardware implementation, and
- Fault tolerance.

Several types of switch architectures are considered below with respect to their performance in a satellite network.

On the satellite, a baseband switch structure is needed to provide full interconnectivity between the uplink and the downlink carriers. The main reason that baseband switching is desirable for the integrated video network is the complexity involved in dynamically switching (at an intermediate frequency) data between a large number of input and output beams. A number of baseband switch structures are possible, with each type being optimal for particular design requirements. Baseband switching architectures can be classified into two types:

- Circuit switched architectures
- Packet switched architectures

In circuit switched architectures, data in a particular time slot or frequency on the uplink is mapped into a different time slot or frequency for transmission on the downlink. This type of switching requires knowledge of a pre-determined circuit path, and typically a reconfiguration of the on-board switch to accommodate changing traffic patterns.

Packet switching, on the other hand, consists of routing traffic through a switch based on discrete blocks (packets) of data. These packets contain an information field and a header which allows the switch fabric to correctly route them to the destination. For slowly varying circuit connections, use of a packet switch would add unnecessary overhead, but for more rapidly varying circuit connections or for packet switched connections, a packet switch is optimal.

Much of the development effort in packet switching has focused on destination directed (fast) packet switching, or switching based solely on the destination address of each packet. This essentially distributes the call control to each switching element, so that global control is not necessary to route the packets. It is important to note that packet switches may route circuit switched traffic by packetizing and depacketizing the data. Circuit switches do not have this capability with packetized traffic.

Several possible satellite on-board switches are realizable, depending on the estimated traffic patterns and the number of downlink beams. For a global downlink beam no processing is required, since every earth station receives all of the traffic. For a limited number of large spot beams, some interconnection is required, generally best realizable with a dynamic space switch architecture. For a large number of small spot beams, the size of a space switch requires much more complex traffic scheduling and a larger number of switch configurations to optimize the efficiency. Rapid reconfiguration of a large space switch poses difficulties at high bit rates.

Traffic patterns also influence the performance of switch architectures. For trunking applications where traffic configurations are not expected to change rapidly, a space switch or TST arrangement (circuit switch) is most suitable. However, for bursty traffic patterns at high bit rates, some type of fast-packet switch architecture will greatly reduce network control complexity.

Four general classes of baseband switches, a circuit switched architecture and three packet switched architectures, are particularly applicable to the general network requirements for integrated video.

1. Circuit Switch: Time-Space-Time
2. Packet Switch: Common Memory
3. Packet Switch: Shared Medium Topology
4. Packet Switch: Space Division Fabric

Several other architectures or variants of these approaches such as those described in [4] may be applicable in the future, but current implementation problems or switch sizes are prohibitive for the integrated video requirements.

In each case, design issues of the switch to be considered include:

- Performance at required bit rates and capacities,
- Efficiency with multicast and broadcast traffic,
- Ease of space-qualified hardware implementation,
- Fault tolerance, and
- Priority control.

4.5.2.1 Circuit Switch: Time-Space-Time

The first baseband switch considered, the Time-Space-Time (TST) switch, is shown in Figure 4-6. This architecture is a commonly used circuit switch, and is also known as a distributed input/output memory switch. Input traffic is time-division multiplexed as it enters the switch input memory. The input memory performs a time-slot interchange before the data is sent to the space switch, where it is routed to the correct output memory. The output memory performs an additional time-slot interchange. In this way, input data is mapped from a particular uplink time slot to a particular downlink time slot in the same or different beams. The mapping is centrally controlled by a switch controller (for a description of TST design considerations, see [5] concerning the ACTS program).

The TST architecture supports circuit switched but not packet switched traffic. It is best suited for slowly varying traffic patterns, since new call connections require reconfigurations for a number of units. Within video services, this architecture would be best suited for video distribution services, such as cable television distribution. Considerable network control complexity is required to provide interactive services such as video conferencing [6]. Multipoint routing could be implemented by performing multiple reads from memory slots in the time stages of the switch. Fault tolerance is best implemented using component redundancy among the memories and space switch.

4.5.2.2 Packet Switch: Common Memory

The second architecture, shown in Figure 4-7, is the Common Memory switch. For circuit switched traffic, the memory can be thought of as a large individual time-slot interchange, as in the TST architecture. This type of switch can also be designed as a packet switch which can be used for both packet switched traffic and circuit switched traffic if the traffic is packetized for switching purposes. The packet-based switch is described below.

Two basic types of memory access are possible:

i. In the sequential write and random read method, incoming packets from all input lines are multi-

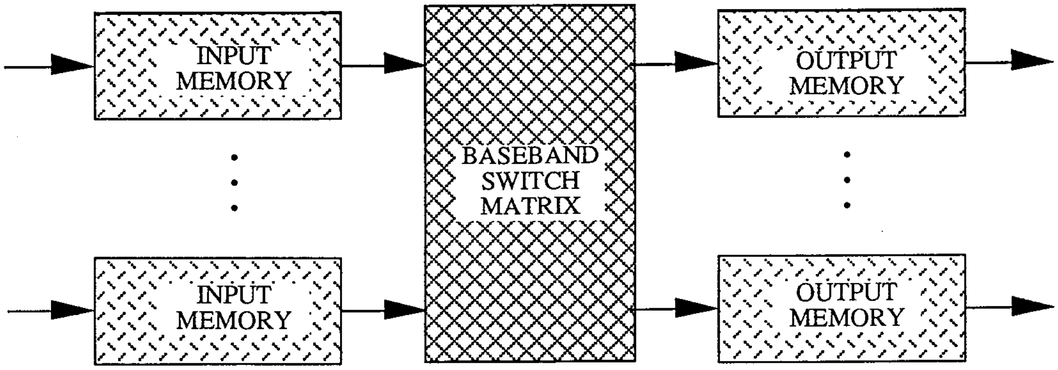

Figure 4–6: Time-Space-Time Switch Architecture Is Commonly Used as a Circuit Switch

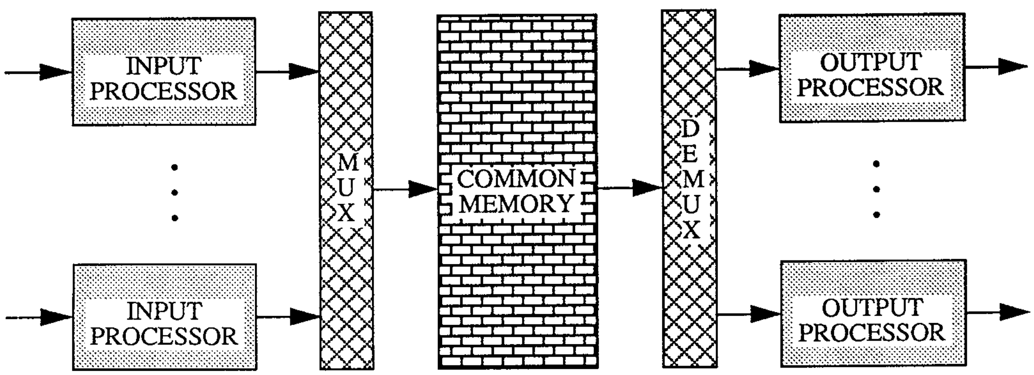

Figure 4–7: Common Memory Switch Architecture

plexed and written sequentially into a common memory. The address (output port destination) of each packet is also stored in a separate control memory. The output TDM stream is formed by selecting packets destined for different output ports on the basis of packet addresses stored in the common memory. The addresses are stored in a separate control memory and are accessed by the memory output in selecting the proper sequential packet.

ii. The random write and sequential read method does not require control memory, but requires a larger data memory. Packets are filtered based on output address and read into partitioned segments of the data memory corresponding to the destination output port. The output TDM stream is then formed by selecting packets sequentially from each memory partition. The data memory in this approach must be larger than that of the first since idle memory locations are not fully shared.

Limiting factors for a common memory switch are the memory access speed and power consumption. For example, using a 64 bit wide memory, a memory with a bandwidth of 3 Gb/s requires a data memory write and read every 20 ns. For large switches, this speed, and the large address fields of each packet, places a large load on both the data and control memory. Furthermore, there may be bus interference problems on the multiplexed input and output lines at high data rates. At capacities exceeding a Gb/s, parallel processing must be implemented. An example of such a design, based on ATM switching, is given in [7].

Multicasting and priority control are easily facilitated in this structure. A separate multicast module can be added which accepts all incoming multicast packets and then makes copies to place into the appropriate memory. Some form of multicast capacity allocation must be used to prevent multicast packets, which have a higher priority than point-to-point packets, from clogging the output ports. In the case of partitioned memory, multicast packets could be written into a separate partition and then written to each output port buffer as needed.

Necessary fault tolerance would essentially include complete or partial redundancy (depending on implementation) for the common and control memories, and partial redundancy for input and output processors. Priority control can be implemented such that packets destined for particular output ports are arranged in either the control or data memory in the form of linked lists corresponding to the priority of the packet.

4.5.2.3 Packet Switch: Shared-Medium Topology

The third approach considered is a shared-medium architecture using output buffering, an example of which is shown in Figure 4-8. The shared medium could be an optical bus or optical ring to which all incoming traffic is multiplexed and from which each output port filters the total traffic for packets destined to it.

This design is an extension of the partitioned common memory discussed above, except that the common memory is replaced by separate FIFO buffers and address filters at each output port. In this approach, all input lines are multiplexed together onto a high speed TDM bus. Address filters on each output line screen the address of each packet, and write the desired packets into a memory, from which the downlink TDM stream is formed.

Two topologies, both of which use optical fiber, exist for implementing the high-bandwidth common medium:

i. Bus topology

ii. Ring topology

In the bus approach, a single high speed bus contains N input and N output taps, and traffic from each input tap is directed onto the fiber. For the optical ring, a token ring format can be adopted, in which a TDM frame circulates around the ring, containing slots for each input port's traffic.

A major limitation to a standard high speed bus is the constraint on the number of taps possible on a single optical link. A possible solution to this limitation would be to use a parallel architecture to distribute the number of ports among several buses, although this type of segmentation greatly increases complexity and would not reduce the number of output taps on each line.

One major advantage of a shared-medium architecture is its inherent multicast capability. Since output lines filter all of the traffic on the bus, multicast packets can be read from the bus by multiple output ports. Such multicast traffic could also be accommodated by a separate multicast output buffer, which could receive all multicast traffic and place it in the proper output buffers. Fault tolerance is also easily implemented through the addition of redundant input and output ports and a redundant bus or ring. Priority control could be accommodated by segmenting the output buffers on the basis of packet priority.

4.5.2.4 Packet Switch: Space-Division Fabric

Space-division switches (Figure 4-9) are characterized by multiple paths from input lines to output lines, instead of the sharing (multiplexing) of many paths. There are two general classes of space-division switches:

i. Crossbar switches

ii. Banyan fabric switches

Crossbar-based fabrics consist of N^2 switching points to accommodate the connection of N input lines to N output lines, provided that the desired connections are disjoint. Packets are routed by enabling the particular (unique) crosspoint connecting the desired input and output lines. These switching decisions are made at each crosspoint based on the address of the packet.

Banyan-based fabrics are also based on the distributed control or self routing of packets through sorting networks. Control is distributed to each switching element, which is able to route the packet correctly based on part of the packet's address.

One advantage of space-division architectures is that switch processing speeds do not necessarily have to be faster than the input line speeds because the switch fabric can route many packets simultaneously. However, multiple paths through the switch architecture may not be able to be simultaneously supported for certain routing patterns. In other words, the switch fabric is said to be internally blocking for certain traffic permutations. Consequently, some kind of output contention resolution must be realized to prevent routing conflicts in the switch fabric.

A second advantage of such architectures is the distributed control of the switch. Switching elements are set based on the incoming packet's address, instead of by a centralized controller. For high speed applications,

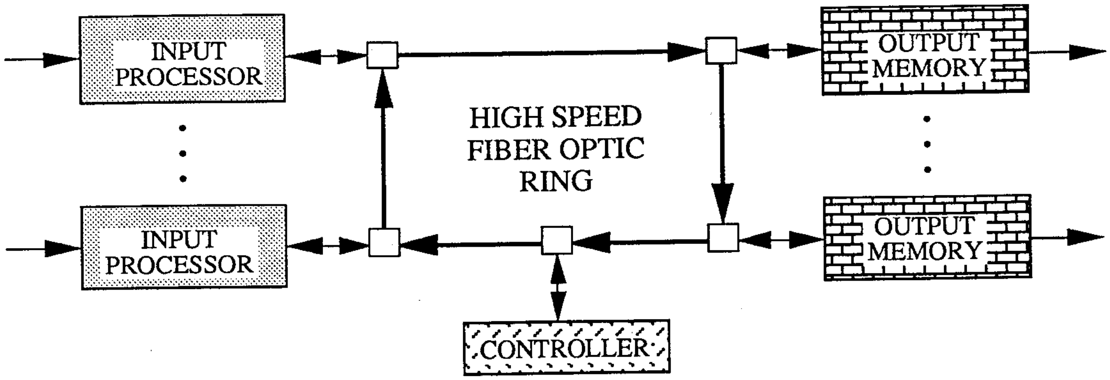

Figure 4–8: Shared Medium Switch Architecture

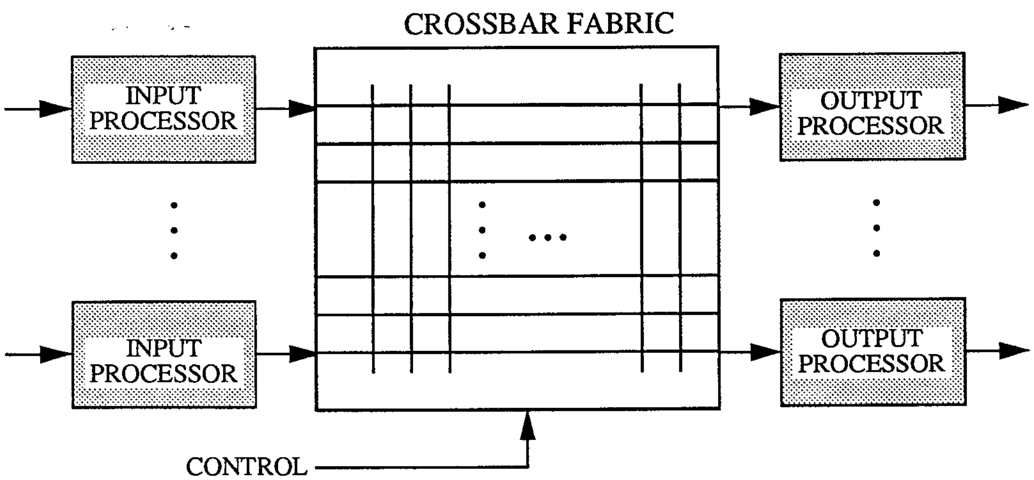

Figure 4–9: Space Division Switch Architecture

such distributed control is advantageous. A disadvantage of such designs are latency problems, or that the delay through the switching fabric is dependent on the connection pattern.

Given that certain traffic patterns block the switch, buffering or packet dropping must be performed at some place in the switch. There are three locations at which packets may be buffered: at the input or output ports, or within the switch fabric.

The most straightforward approach is to buffer packets at the crosspoints or switching elements within the switch fabric. This method, though, is not memory-conserving, since the memory is distributed throughout a number of different locations, and presents implementation complexity in designing the switch fabric.

Input buffering, with an arbiter to determine acceptable traffic permutations, is also a possibility, but unless methods are undertaken to efficiently extract packets out of the buffers, throughput will be low due to blocking at the front of the packet queues.

Finally, output buffering is the most throughput efficient, but requires additional complexity or the operation of the switch fabric at a much greater rate than the incoming line speeds; each packet is routed through the fabric individually. *For switching fabrics limited by speed, input buffering appears to be the best choice.*

Space-division switches are designed for point-to-point routing. To accommodate multicast traffic, some modifications must be made. Multicast packets may be duplicated at the input or output side of the switch fabric, or within the fabric itself. If packets are duplicated on the input side or within the switch fabric, they must be able to reserve those multiple paths through the switch, or else blocking will occur. Otherwise, packets may be routed to a special multicast port, which duplicates the packets as needed and places them in output buffers.

Fault tolerance is best implemented by providing for redundant, unused paths through the switch fabric which can be activated as necessary, and by providing redundant input and output ports. Graceful degradation is good in such structures, since a point failure in a part of the switch only affects one particular connection. Priority control can be maintained by partitioning the buffers according to packet priority, as discussed above.

4.5.3 Satellite Processing Description for Selected Design

The baseband switch and network architectures described above all offer certain advantages and disadvantages and are suited for some applications better than others. In the following section, a candidate baseband switch architecture is developed in detail. The particular architecture selected offers efficient performance under the general network requirements set forth above.

4.5.3.1 Overview

A block diagram of a candidate architecture is provided in Figure 4-10. This architecture is an extension of the shared-medium architecture discussed in ¶4.5.2.3, in which continental U. S. (CONUS) coverage is provided by 28 fixed spot beams on the uplink and downlink. The access method is TDMA on the uplinks and TDM on the downlinks. With a variable information capacity rate from 36 Mb/s to 108 Mb/s in each beam, the system is intended to provide an information capacity of 3 Gb/s. On the uplink, carrier rates are either 2 Mb/s or 6 Mb/s; users may access the carriers up to their full capacity. With this arrangement, as described below, the system occupies, on both the uplink and the downlink, 1.1 GHz of bandwidth at Ka-band.

Video services are primarily circuit switched services. However, the proposed network architecture is based on packet switching The packet switched architecture selected is easily able to accommodate circuit switched traffic by packetizing the data. Furthermore, the chosen design effectively handles multipoint traffic. Within the satellite network, routing is performed on the basis of packet headers. All traffic is converted into this packet format for the duration of the satellite link. Although the network internally is based on packet switching, externally it can be treated as a circuit switched network.

As shown in Figure 4-10, the multicarrier baseband signal from each beam is demodulated by a MCD and then sent to an input processor. The input processor decodes and descrambles the data, and assembles and buffers the packets for the switch. After the switch routes the data to the correct output processor, the packets are scrambled and coded before being modulated for retransmission. Control of the network is provided by a network control station which monitors the payload for fault diagnostic purposes and also provides capacity allocation for the system through the network controller.

In the sections below, key components of the design are more fully described. This architecture makes use of the Mesh VSAT Study [8] design because the general network design requirements are similar in terms of capacity and connectivity.

4.5.3.2 Input Processor

The input processor is responsible for preparing the incoming demodulated data for transmission through the fast-packet switch. There are 28 input processors (one for each beam). A block diagram is shown in Figure 4-11. Data from three MCDs are 32-bit multiplexed to form carrier blocks of 32 bits each. These blocks are decoded by the FEC decoder and differential decoder to form carrier blocks of 8 bits each (a factor of 4 reduction from the redundancy and the 2-bit soft decision). Packet assemblers construct the 1024-bit satellite packets in a buffer that holds two packets of data for each carrier. The data is then descrambled, deinterleaved, and buffered before entering the optical bus interface.

Within the packet header there is a header error check (HEC) field, which functions much the same as an ATM cell header error check. Each packet header is examined for 1-bit correctable errors or other detectable errors. Because the packets are interleaved by a 1024-bit scrambler, burst errors in the header will likely be distributed as 1-bit errors through many packets, which the HEC will be able to correct.

The optical ring interface is shown in conjunction with a packet buffer that groups sets of 18 packets together for insertion in the proper field of the frame. This optical bus interface provides timing signals to other parts of the input processor for synchronization.

4.5.3.3 Baseband Switch

For the proposed design, a high-speed optic ring baseband switch has been selected (Figure 4-8, ¶4.5.2.3). This switch has a number of attributes that lend it particularly well to the expected traffic demands of integrated

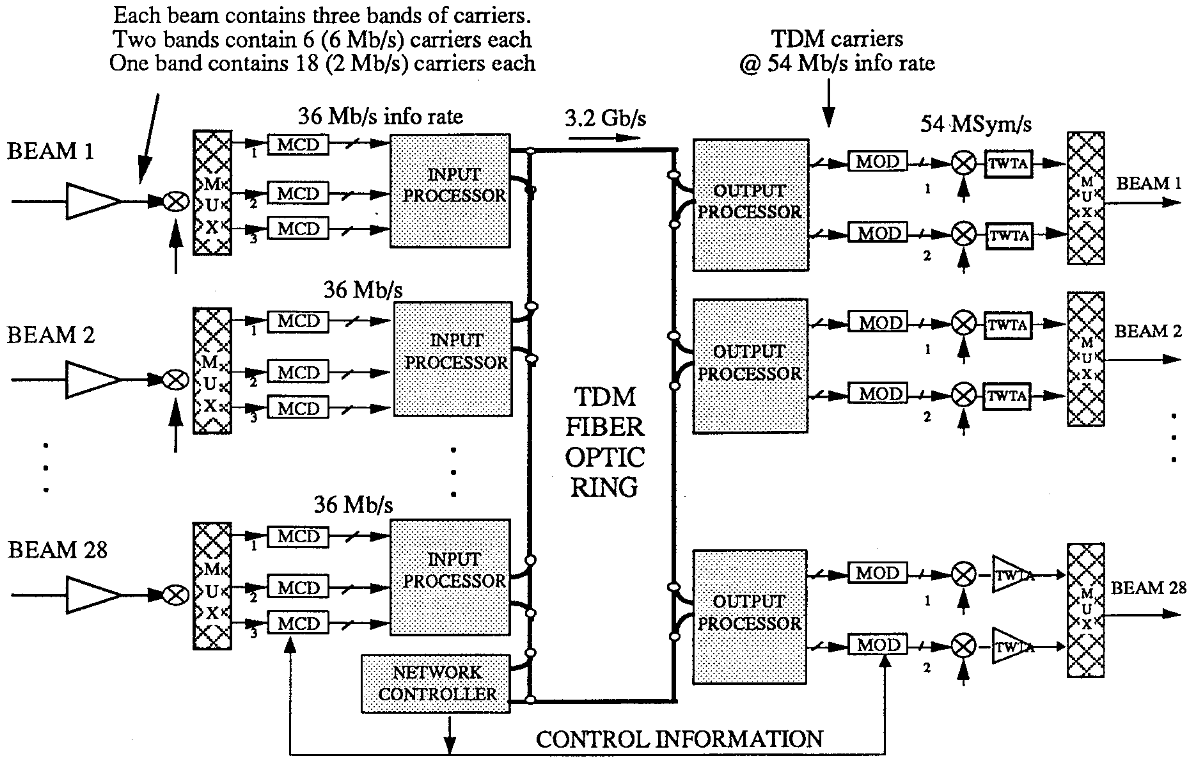

Figure 4–10: Block Diagram of Baseband Processor

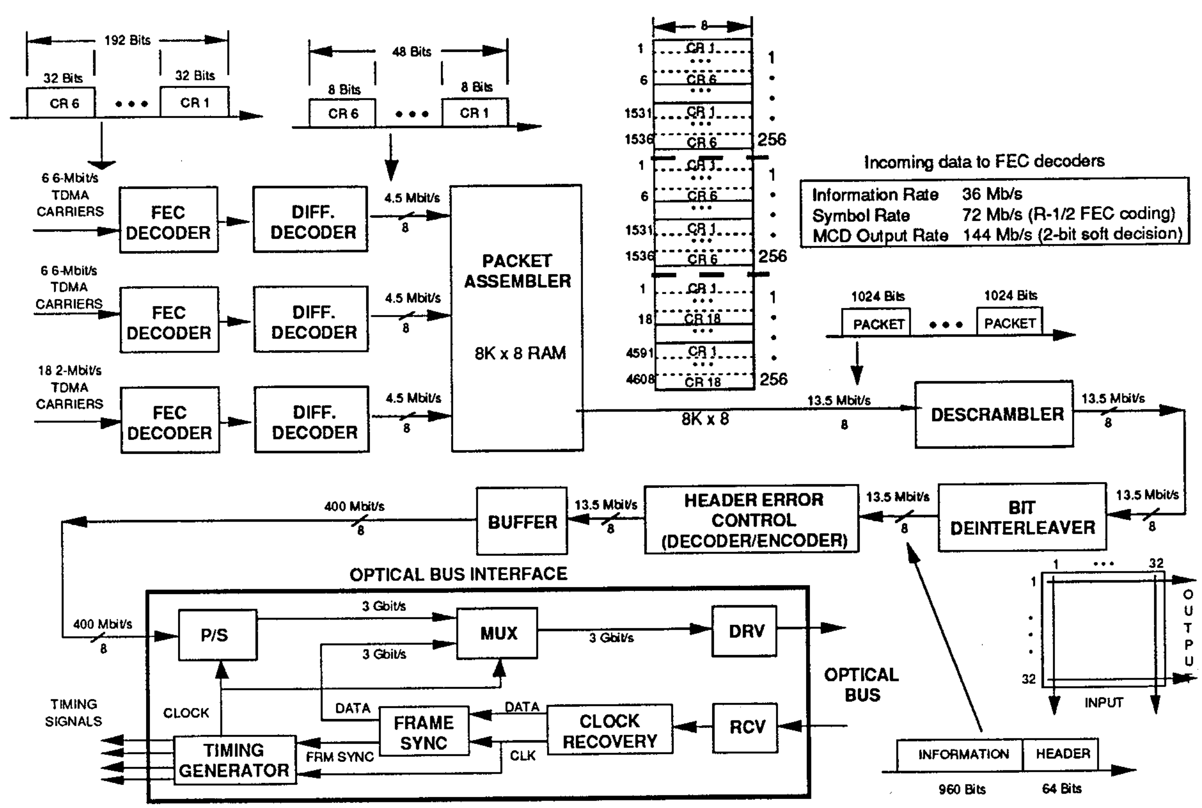

Figure 4–11: Block Diagram of Input Processor

video. Most importantly, the topology has an inherent multicast capability, which is an important network feature for video services. Other attributes of this switch include a simpler interface among processing units, a self-routing control algorithm, no control memory requirements, and a modular design for redundancy and flexibility. The switch can function at the desired capacity of 3 Gb/s.

Figure 4-12 shows a block diagram of the switch architecture. The optic ring consists of interfaces with 28 input processors and 28 output processors, and an autonomous network controller. The interfaces to the processors contain a bypass switch, used for redundancy and fault tolerance purposes. Should an input processor fail, the switch will bypass the processor. The data frame is regenerated at each interface, as illustrated in the input and output processor block diagrams.

Data travels around the ring via a 250 μs data frame. Within this frame, there are fields for control information and for packets from each of the 28 input processors. This frame size and period are sufficient to fully handle the capacity of the input processors. Each time the frame is circulated, each input processor places the contents of 29 packets within its field in the frame. These packets are synchronized to a common ring clock. Each output processor receives all of the traffic and filters each frame for its packets. Because of the added control information which circulates along with the data, the data rate on the optical ring is approximately 3.4 Gb/s.

The ring is maintained by an autonomous network controller (ANC), which is responsible for frame maintenance, clocking, ring control, and signaling. Control signals are exchanged between the processors and the ANC through the control field header on each frame.

4.5.3.4 Output Processor

The output processor extracts and reformats only the packets addressed to its corresponding downlink beam. A block diagram of the output processor is shown in Figure 4-13. There are 28 output processors for 56 downlink carriers, so each processor assembles two TDM frames for modulation. The entire optic data frame is filtered for packets on the basis of two address bits:

- One bit in a field of 32 specifies the proper output processor, and
- An additional bit specifies one of the two output lines from that processor.

The address filter located at the output of the optical bus interface performs packet extraction according to the routing information contained in the packet headers. The extracted packets are stored in a frame buffer for formatting. The two bit streams from the frame buffer (forming two carriers) are bit-interleaved to protect packet headers from burst errors, scrambles, and FEC encoded for downlink modulation.

4.6 Synchronization

The synchronization of data arriving from different sources with a TDMA access method is made more complicated by the variation in satellite position caused by orbital drift. The effects of variable path lengths and different user clocks are accentuated by high bit rate traffic. Two basic methods exist for synchronizing user clocks:

- Bit synchronous system synchronizes user clocks to the on-board clock within a fraction of a symbol period (see Figure 4-15).
- Asynchronous system uses asynchronous user clocks. This method is selected for the Integrated Video system for the reasons explained below.

An asynchronous system requires timing adjustments for each carrier, accomplished by preambles affixed to each burst. Preambles and the guard times between asynchronous bursts lower the uplink frame efficiency. This is shown in Figure 4-14 by the comparison of bit synchronous and conventional frames.

A bit synchronous system does not require preambles and guard times, resulting in higher TDMA frame efficiency and simpler demodulation techniques. A disadvantage, though, is that timing phase data storage is needed on-board for individual user terminals, and that user terminals must then achieve precision timing to stay in synchronization (see Figure 4-15).

Bit synchronous systems also present problems for random access schemes, in which the signals source is not known until the signal has been received. This synchronization may also be difficult at carrier bit rates such as 6 Mb/s. Despite the current limitations, development of a bit synchronous system for higher rate carriers is encouraged because of improved frame efficiency.

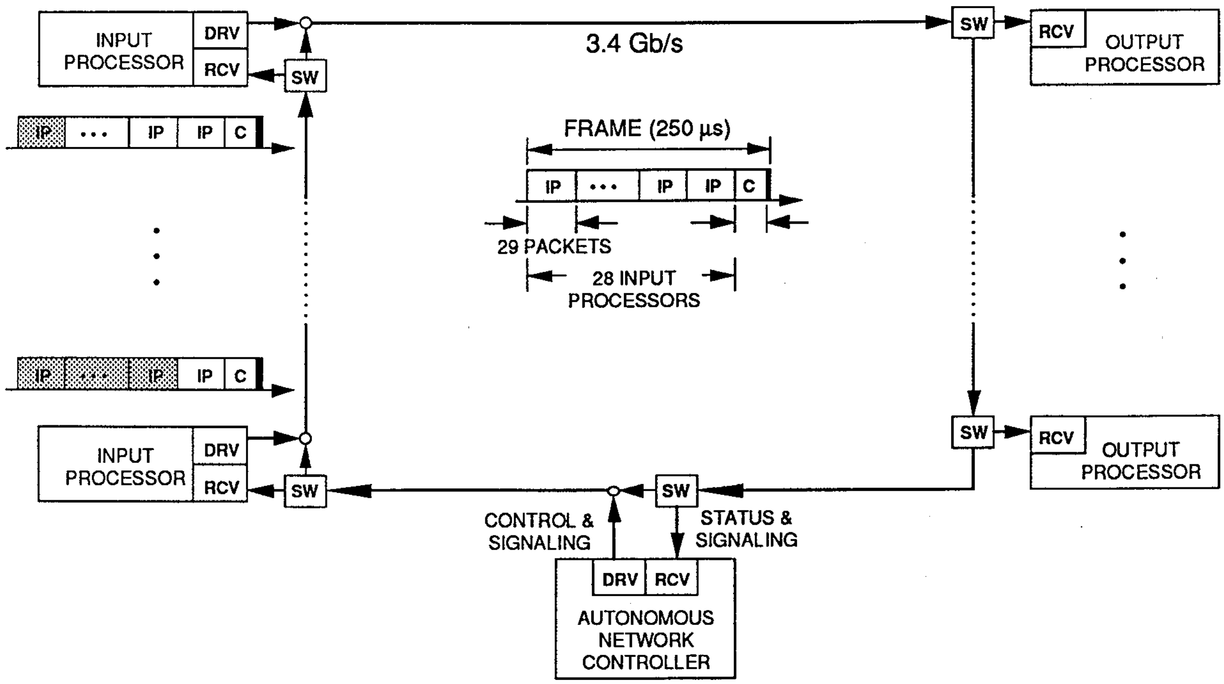

Figure 4–12: Block Diagram of Switch Architecture

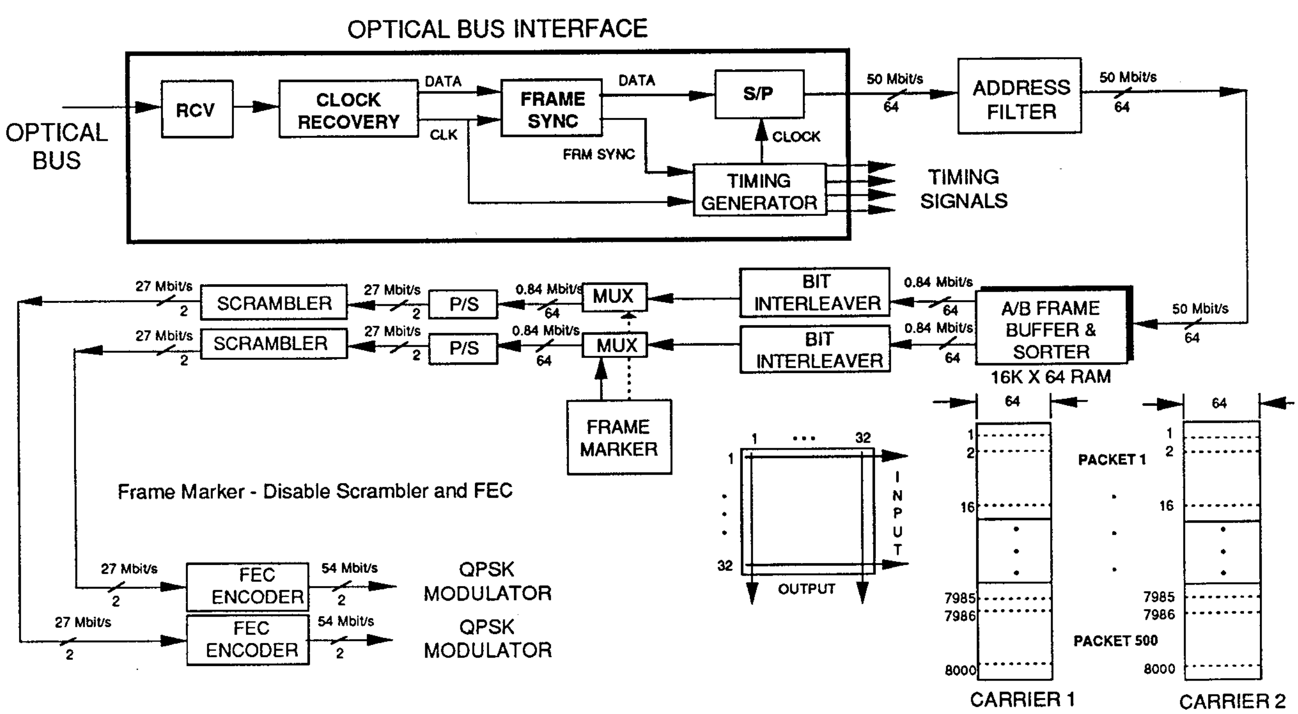

Figure 4–13: Block Diagram of Output Processor

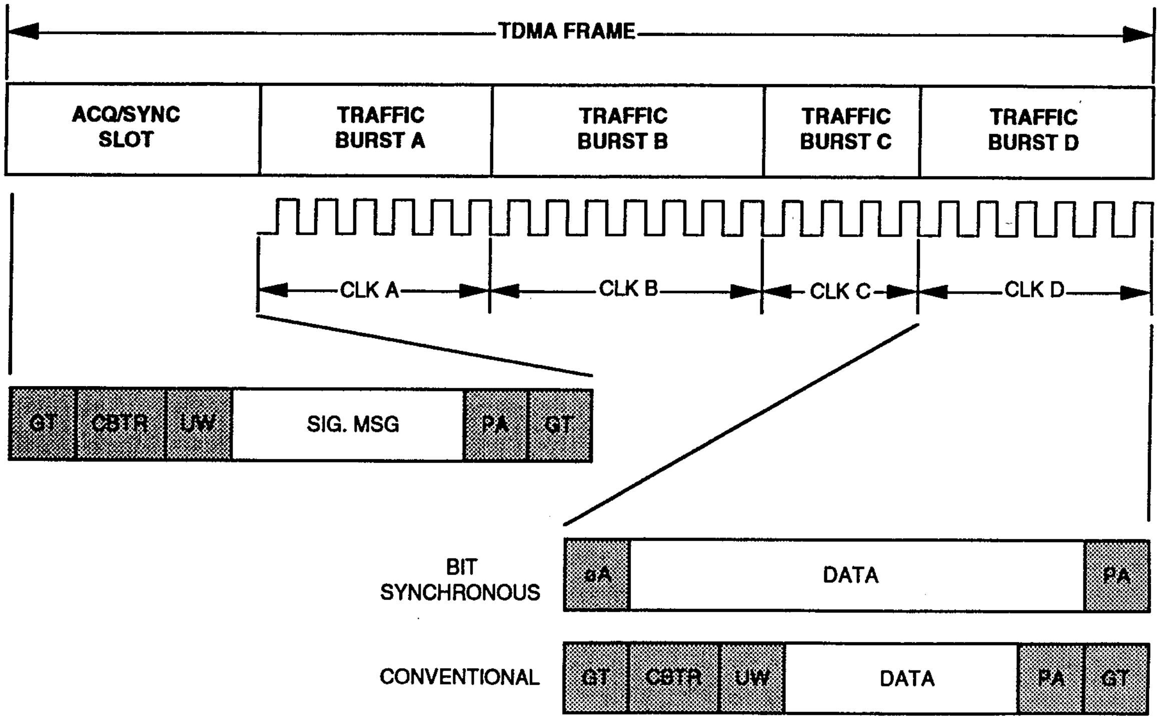

Figure 4–14: Bit Synchronous TDMA Frame is More Efficient

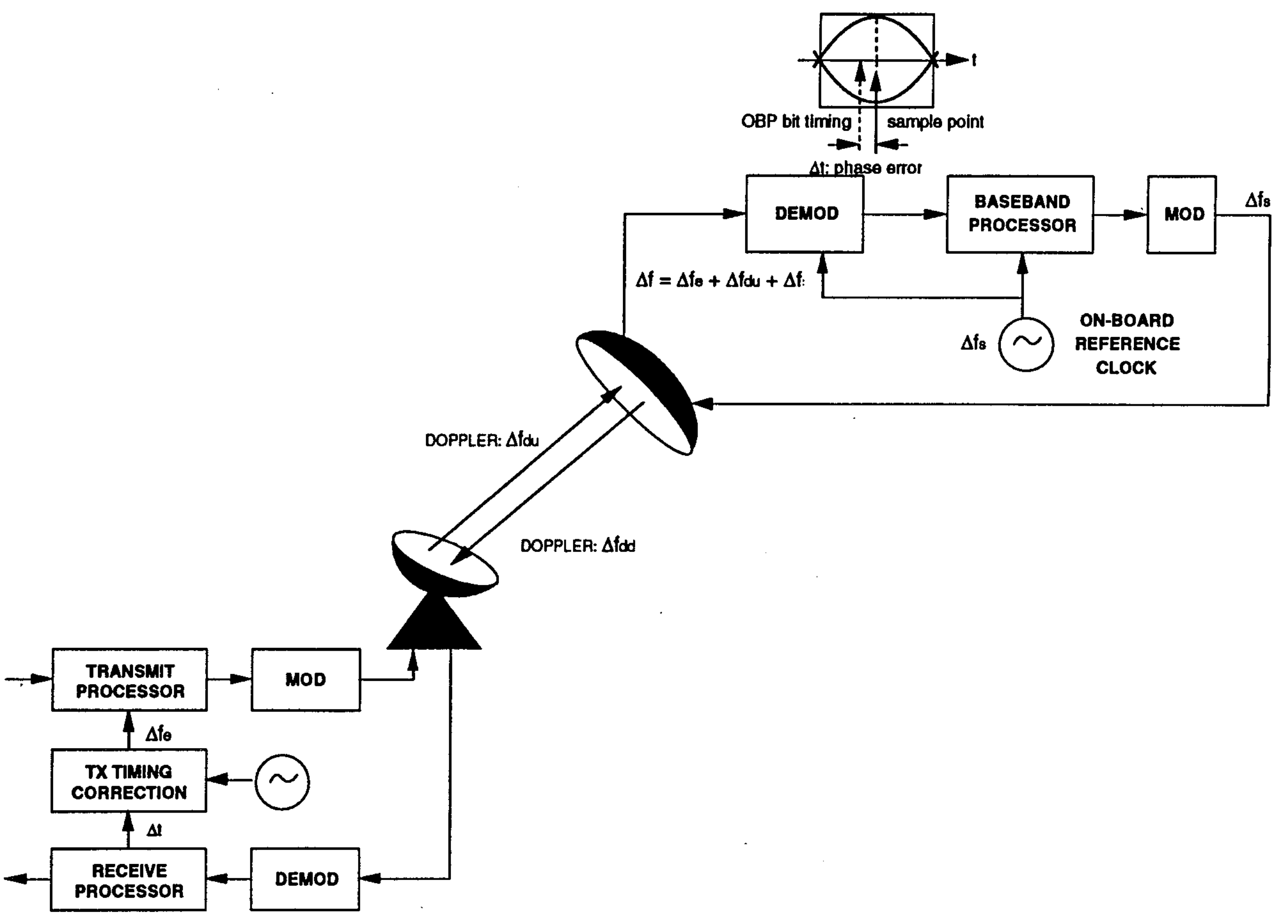

Figure 4–15: All Earth Station Clocks Are Synchronized at the Satellite in a Bit Synchronous System

In bit synchronous systems, two types of network synchronization are possible:

- Open loop synchronization
- Closed loop synchronization

In open loop synchronization, user timing is determined on the basis of a received reference clock and knowledge of the satellite position for delay adjustment.

Closed loop synchronization is a feedback oriented system in which the satellite measures received phase errors and feeds back this information to the terminal. Closed loop synchronization is preferred because the requirement of accurate satellite ranging is difficult. Effective synchronization methods must be developed to handle high bit rate, multiple access systems.

Phase ambiguity resolution must also be performed for demodulation. There are several methods:

i. The phase estimation can be accomplished by using differentially coherent modulation, which does not require an absolute phase reference.

ii. Another method is to use a differential code which is insensitive to phase ambiguity.

iii. Estimation may be obtained from a preamble pattern and resolution algorithm. This approach does not apply if the system uses a bit synchronous system in order to avoid such preambles in the uplink TDMA time slots.

In the proposed system, differential coding (ii.) is used to resolve phase ambiguity.

Although a bit synchronous system is preferred for the integrated video network, such a system may be difficult to implement at carrier rates of up to 6 Mb/s. Consequently, *burst preambles (asynchronous system) are required, which lowers uplink frame efficiency. Differential encoding is used to resolves phase ambiguity.* This reduces the number of symbols required for synchronization.

4.7 Signaling and Network Access

Signaling for videotelephony and videoconferencing has not yet been defined by CCITT. Study Group I is currently developing Stage 1 service descriptions for these services (Draft Rec. F.720 and F.730). Once this is complete, Study Group XI will define signaling requirements and develop signaling protocols for Stages 2 and 3. Additionally, no multipoint capability currently exists in DSS1 or SS No. 7 signaling. Such standards need to be developed in order to specify signaling protocols for the Integrated Video Network.

4.7.1 Access Techniques

In the satellite system, a network controller interacts with user earth stations for network access, capacity requests, channel/bandwidth allocation, and earth station monitoring and control. A number of alternatives exist for providing signaling channels between user earth stations and the network controller:

- One possible technique is to connect the network control station with the user earth stations via a terrestrial link. This method may be desirable if there are no occasions or locations from which terrestrial access is not possible.

- The other option is to provide the network controller access via a satellite link. This option permits implementation of on-board autonomous network control, in which many network control functions are located on-board the satellite.

This access may be accomplished in-band or out-of-band. Access requests may be transmitted on out-of-band signaling channels, such as with a narrowband TDMA or random access channel used exclusively for signaling. Otherwise, an in-band technique could utilize a portion of a TDMA or TDM frame for signaling.

For example, in this TDMA based system, signaling packets could be transmitted in one of the time slots accessed on a random access basis. This random access time slot could also be used for TDMA acquisition by reducing the packet length to increase the effective guard time on each side of the burst. The time slots could also be implemented as coordinated access time slots if the number of earth stations is not too large and the delay in waiting for access is acceptable.

Upon receipt of a signaling request by a particular earth station, the network control station allocates one or more time slots to that earth station and transmit this notification via a signaling message packet. While it maintains a connection, an earth station uses its allocated time slots or the random access slot for subsequent signaling packets.

4.7.2 Multicast Traffic

In the integrated video environment, point to multipoint signaling is necessary. The signaling system is responsible for dynamically changing connection configurations in real time. For example, in a video conference, the video signal may frequently switch between users, while audio signals may be mixed together as in a conference call. As signaling protocols for video conference setup and management are developed by CCITT and other standards bodies it will be necessary to account for satellite propagation delays.

Real time switching must be accommodated as well. For example, a participant may want to join into a conference in the middle of a session. The signaling protocol must be able to add or drop users in the middle of a connection. Development of multicast signaling protocols to manage videoconferences will need to account for satellite propagation delays.

Multicast traffic, or (multi)point-to-multipoint traffic, will likely be a large segment of video services in the future, since satellite network topologies have an inherent multicast capability. From a satellite standpoint, there are two means of providing multicast service:

- Multiple copy transmission, and
- On-board multipoint routing.

The latter type of routing is more bandwidth efficient, since the traffic need only be duplicated for the downlinks, and not for the uplinks. In order to provide this routing, multicast packet switching and a multipoint signaling protocol must be provided between users. In either case, on-board multicast routing leads to larger overheads and the development of multipoint switch structures and protocols.

If on-board multicast routing is not used, multiple copies may be duplicated on the ground and transmitted separately on the uplinks. This approach lessens the on-board complexity required by the satellite, but at a cost of less efficient uplink bandwidth utilization.

4.7.3 Other Signaling Issues

Protocols used in video networks must either perform well under space segment operations or else be modified or terminated at the earth station. In setting up and maintaining a connection between earth stations, the satellite network may either pass the standard video signaling (possibly with slight modifications) or it may terminate it and issue its own signaling messages. It is advantageous to make use of the existing signaling protocols if possible, in order to lighten the processing load at the earth stations. However, some protocols may not be suitable for satellite applications, and will need to undergo interworking functions such as protocol conversion.

Typically, acknowledgement timers and flow control mechanisms may need to be adjusted on a protocol to adapt it to satellite communications. This may be done by sending signals back upstream from the satellite network to the terrestrial nodes to notify it that the traffic has entered a satellite link. If this is not possible, the protocol may need to be terminated at the interface between the terrestrial and satellite network.

Additionally, steps must be taken to avoid multiple hops in a satellite network. This feature is very important in an integrated video network due to the effect of delay on real-time services. The presence of a satellite link within a particular circuit is given by a satellite indicator field in some protocols such as SS No. 7, but not in others such as Q.931. In this network architecture, the satellite interconnects users, or connects users to a terrestrial network node. If SS No 7 is used as the network signaling protocol, the presence of the satellite link is indicated in the initial address message (IAM) for any future routing decisions. A decision on whether or not to allow a call, possibly based on the connections quality of service (QOS) parameter, must be made in the case of an incoming call that has already been on a satellite link. Also, it may occur that the circuit is unavoidably forced to traverse a satellite link twice to make a connection. In such cases, decisions must be made as to whether to accept such a call, based on QOS specifications.

Another signaling issue consists of whether audio and visual signals travel on different paths. This may present a problem due to synchronization of voice with video. The possibility of such routing arises from the fact that the video and audio services are not symmetrical. For example, a teleconference participant may receive video from only one other participant but receive audio from all participants simultaneously.

4.8 Frame Formats and Protocols

Figures 4-16 and 4-17 illustrate the uplink TDMA and downlink TDM frame structures. On both links, the time slots are sized so that one time slot contains a large enough information field to support a 64 kb/s connection. As discussed above in ¶4.5.2, although video services are primarily circuit switched, this design employs packet switching for distributed switching control purposes. Consequently, circuit switched traffic must be packetized and assigned a header.

Figure 4-16 illustrates the format of the packet header and the uplink TDMA frame.

- The first two fields contain addresses for the destination output port on the satellite link. Traffic is filtered by the output processors on the basis of one bit in a 32-bit field, and then these packets are stored for input to a modulator on the basis of a second bit.

- Next in the header field is a 10-bit destination address, used by each downlink earth station to filter packets from the downlink TDM stream.

- The connection ID field allows for 2^{13}=8192 distinct virtual connections, assigned on a global basis within the satellite network.

- Finally, there is a control bit for indicating the presence of a signaling or traffic packet, and a 7-bit header error check (a CRC checksum).

The header contents (except for the checksum) are assigned by the network controller at the time of connection setup.

Each earth station will generally support more than one 64 kb/s connection, and will transmit a number of contiguous packets in each frame. In order to simplify the on-board demodulators, at the expense of some frame efficiency, it is proposed that each packet be treated as a separate burst and be affixed a burst preamble for synchronization, instead of just affixing the preamble in front of an earth station's contiguous packets. As a result, the demodulators do not need to be reprogrammed for each call setup. Because of the use of differential coding, carrier phase ambiguity can be resolved by the differential decoder, but the burst preamble must contain carrier bit timing resolution.

If in-band acquisition and signaling are used, a portion of the frame must be allotted for signaling and acquisition packets. Each of these packets must be preceded by a burst preamble for synchronization. The size of the random access or coordinated access window is a design issue that is discussed briefly below.

On the downlink, the TDM frame period should be the same as the uplink period to prevent imbalances between uplink and downlink transmissions. Each frame (see Figure 4-17) contains a reference burst followed by fields of packets for different earth stations. The reference burst contains a frame marker, signalling field (acquisition indicator) to alert user terminals, a frame number, and a header error check. The acquisition indicator could be used to identify when an earth station may attempt transmit acquisition within the uplink signalling window on the next frame. It may also contain timing correction information for earth stations. Burst preambles and guard times are not needed for the downlink. All of the TDM frame consists of coded information, so that the decoders may operate continuously.

As shown in Figure 4-16, each 15 ms uplink frame contains 32 or 96 time slots, one of which is reserved for signaling. Each time slot contains 960 bits uncoded, or 1920 bits coded (960 symbols assuming QPSK), which corresponds to a 64 kb/s channel. Including packet overhead, each time slot contains 2048 coded bits for 1024 symbols, and 96 uncoded symbols for synchronization. The frame efficiency is approximately 83% (31/32 * 960 symbols/1120 symbols) for the 2 Mb/s carriers, and 85% (95/96 * 960 symbols/1120 symbols) for the 6 Mb/s carriers. The actual carrier information rates are 1.984 Mb/s (31 * 64 kb/s) and 6.080 Mb/s (95 * 64 kb/s). The transmission rates are, respectively, 2.39 Msym/s (1120 sym*32/15 ms) and 7.168 Msym/s (1120 sym*96/15 ms).

On the uplink TDMA frame, the last time slot is reserved for signaling packets. In general, under a coordinated access scheme, earth stations have access to the slot in turn, during which time they may transmit a signaling packet or attempt transmit acquisition. Under the frame structure discussed above, this window is approximately 170 μs long in the 6 Mb/s carrier. Assuming a guard time of 60 μs (for stations that may not have accurate satellite ranging information when they acquire), a signaling packet of approximately 750 symbols can be accommodated. The exact format and size of this signaling packet needs to be investigated, but there should be sufficient time available in one slot to successfully insert a packet from a station that does not have accurate timing correction information.

On the downlink (Figure 4-17), each TDM frame has an information rate of 54 Mb/s. Assuming the same packet structure and frame period as on the uplinks, this results in 848 time slots, with 2 time slots

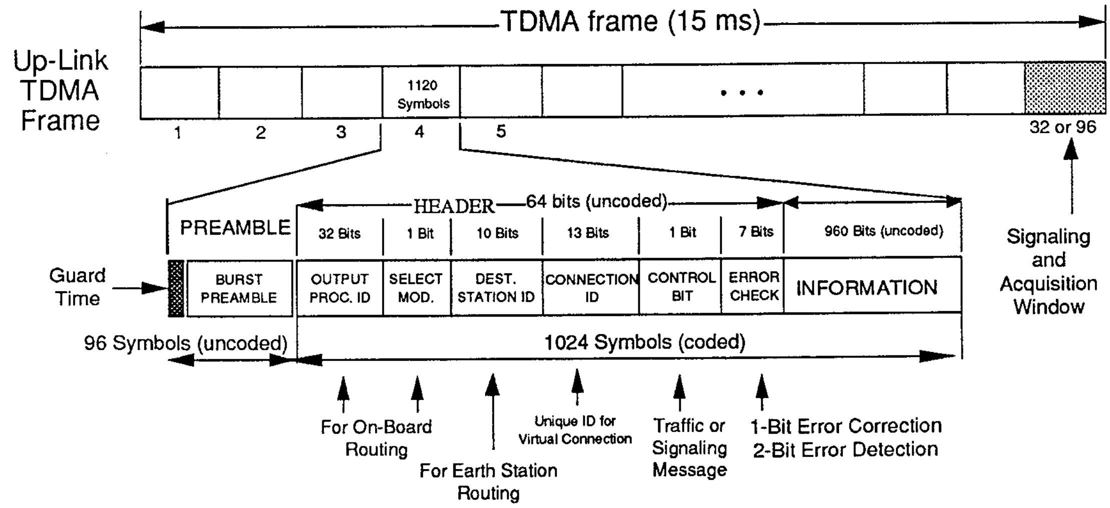

Figure 4–16: Uplink TDMA Frame Format

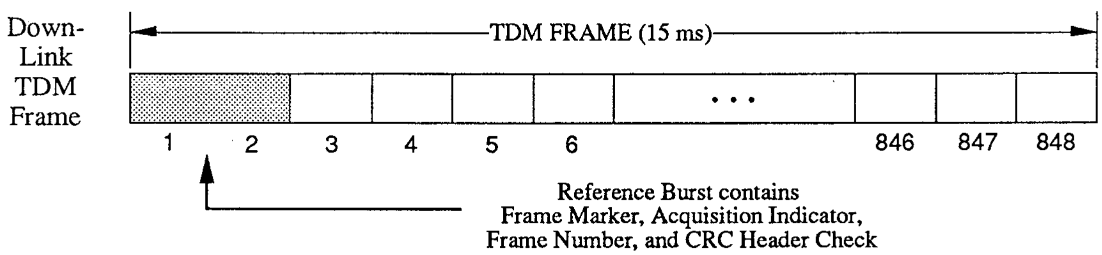

Figure 4–17: Downlink TDM Frame Format

used for the reference burst and signaling information. The downlink frame efficiency is then 93.5% (846/848 * 960/1024). The actual carrier information rate is 54.144 Mb/s (846 * 64 kb/s) and the transmission rate is 57.9 Msym/s (848*1024 sym/15 ms).

4.9 Earth Station Processing

A block diagram of the required subsystems for a user terminal is shown in Figure 4-18. The earth station essentially consists of two parts:

- Terrestrial interface equipment and
- Transmission equipment.

The bulk of the processing occurs at the terrestrial interface. Traffic enters the interface, where it is split according to signaling and traffic classifications. Signaling requests are interpreted by the processor and forwarded to the satellite network controller.

These signaling messages are appropriately packetized before being presented to the TDMA controller, which handles them accordingly. Traffic, on the other hand, is packetized with the appropriate header and then sent to a doppler buffer to await transmission.

On the transmission side, the TDMA controller receives packets both from the doppler buffer and from the signaling processor. Through a closed loop synchronization system, it formats the frame and inserts packets into the frame.

In general, each terminal transmits on only one carrier, but multiple frequency operation could be employed if more capacity is needed. The carrier is then scrambled, differentially encoded, then FEC encoded and modulated for transmission. The reverse process is performed on the downlink except for the differential coding.

With spot beams of 0.87°, user terminals may range in size from 1.2 to 3 m and in power output from 4 to 12 W. The size and power requirements change based on geographic location and desired availability. Link budget calculations are presented in Appendix B.

4.10 Network Control Functions

Network control is divided between an on-board network controller and a network control station (NCS) in one of the beams. Ideally, all network capacity management and fault diagnosis could be performed on the satellite. One of the tradeoffs in designing the control system is providing network control on-board the satellite, where propagation delays can be avoided, versus the increase in complexity in providing such control. This issue could be explored in greater detail once certain signaling aspects and traffic scenarios are completed.

With the traffic load of the system, it is expected that the processing load on the satellite would be too great to centralize the capacity management on-board. Therefore, *it is assumed that the NCS handles capacity allocations for the network.* Additionally, the NCS could function as the TT&C site for the spacecraft.

The NCS handles allocation of satellite capacity on a call-by-call basis. It does so by monitoring the carrier availability in both the uplink and the downlink beams. It also checks the occupancy in the buffers at the source terminal, the output processor on the switch, and the destination terminal. Periodically, the network controller may change the time slot plan and frequency assignments at the request of one of the earth stations or to better distribute network resources and to provide congestion control relief for one of the buffers. Because of the self-routing packet switch structure, though, on-board switch reconfiguration on a call-by-call basis is not required. In general, congestion control is only necessary to support packet switched services.

In the case of a call request, the NCS first receives the request and then forwards it to the destination if the capacity is available. The requested capacity is then reserved, pending confirmation. If the call is accepted by the destination, the NCS forwards the confirmation, along with time slot assignments and packet header assignments, to both the source and destination earth station. One particular advantage that may be gained by placing this capacity assignment on-board the satellite would be a reduction in the propagation delay caused by the double hop to the NCS each way to a single hop each way.

4.11 Mass and Power Estimates

Preliminary mass and power requirements are estimated for the time frame 1996–2000 and are based on a mix of current and anticipated technologies. Digital device technologies used are GaAs for high-speed processing, such as fiber-optic interface processing, and high-density CMOS for other processing functions and memory. Current GaAs technology offers 0.1 mW of power/gate and 50,000 usable gate density. Radiation hard HCMOS offers 12 μW/MHz of power/gate, 50,000 usable gate density, and a speed of up to 400 Mb/s. A 50% reduction in power/gate consumption is assumed for the above time frame.

Most processing functions required in the sample design can be implemented using current technology and are regarded as low risk. Critical technology developments include the following:

- Low-power polyphase MCD with a 36 Mb/s capacity,
- High speed multicarrier Viterbi decoder, and
- 16 K by 32 static RAM.

As mentioned in [2], there are currently a number of development efforts in the area of MCD technology. It is anticipated that MCDs capable of our design requirements will be developed with a power consumption of under 10 W within this decade.

A high-speed programmable Viterbi decoder operating at above 100 Mb/s has been implemented by COMSAT Laboratories using custom add-compare-select logic. Although it currently requires several chips to implement the desired function, a single chip fabrication with a power consumption of less than 1 W is within the technology forecast.

Advancements in radiation-hard memory technology are also expected to improve significantly in the coming years. Current sizes of 8 K by 8 or 16 K by 32 are expected to increase to 16 K by 32 or larger. A conservative assumption of 16K by 32 static RAMs is used for these estimates, although a size of 16K by 64 would reduce the parts count further and improve reliability.

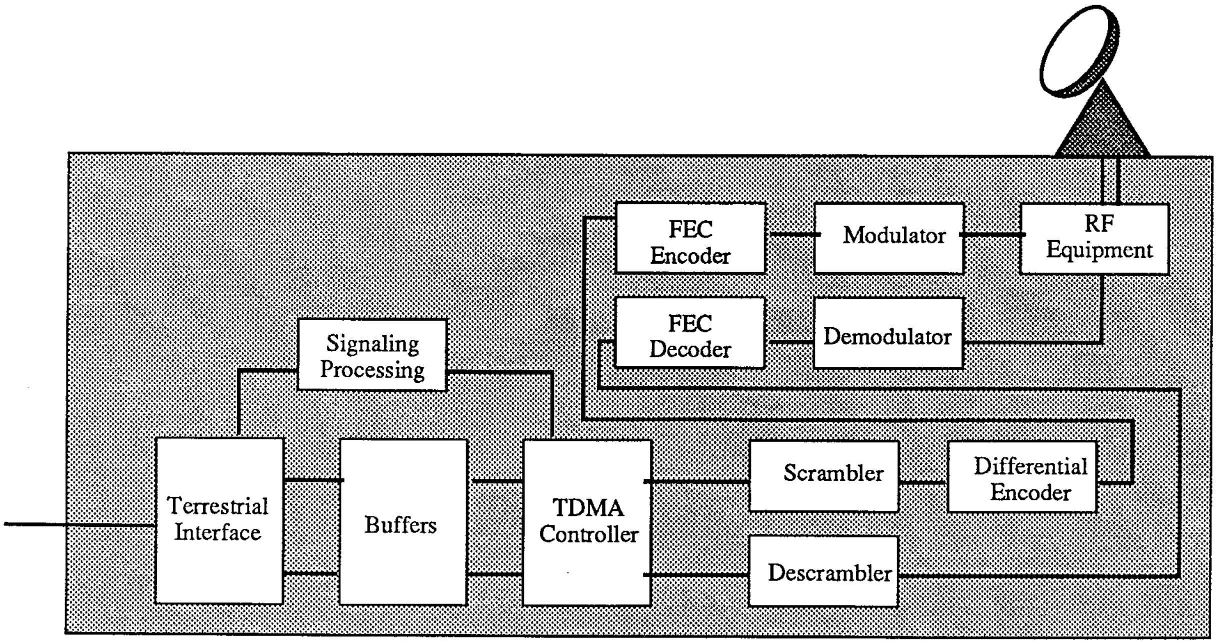

Figure 4–18: Earth Station Block Diagram

The estimated mass and power consumption of the sample design is shown in Table 4-2. This design includes 84 MCDs, 56 modulators, 60 input processors, 28 output processors, a fully-redundant network controller, and power supply. The on-board baseband processor consumes about 874 W of power and weighs 104 kg using technology available in the years 1996–2000. The sample design assumes extensive use of ASIC devices, requiring clock speeds ranging from 1 MHz in the input processors to 3.2 GHz for the optical interface.

4.12 Critical Design Issues

4.12.1 Low-Power MCD

The most critical element in the design appears to be a low-power consumption multicarrier demodulator. Even under the technology assumptions used in producing the estimates in Table 4-2, the MCDs still consume 65% of the power in the baseband processor. Intensive development efforts to reduce the MCD power consumption to the range of several watts is highly recommended.

4.12.2 Bit Synchronous System

In a multicarrier access environment, a bit synchronous system improves frame efficiency and simplifies network design. However, the MCD is required to measure a phase error with an accuracy of a small fraction of a symbol period. It also requires the user terminal to perform accurate timing correction. Alternate techniques to implement a bit synchronous system at these carrier rates should be investigated, and a proof-of-concept model to demonstrate its feasibility should be developed. (See ¶4.6 for more discussion.)

4.12.3 Multicarrier Viterbi Decoder

A high-speed multicarrier Viterbi decoder also requires development. Because a convolutional decoder incorporates memory in its decisions, a large constraint length code is difficult to implement at high speeds. The rate 1/2 code suggested here may be replaced by another code which offers higher coding gain and ease of implementation.

4.12.4 Signaling and Control Issues

Numerous signaling and control issues, some of which are mentioned above, must be considered. Further study is recommended in the area of autonomous network control, as well as in areas concerning the baseband switch (such as optimal buffer sizes and packet transmission formats). Finally, multicast signaling protocols must be developed to meet the needs of integrated video users.

Table 4–2: Estimated Mass and Power Requirements for Baseband Processor

	Mass (kg)			Power (W)			
Equipment	Qty.	Unit	Total	Qty.	Unit	Total	Comments
MCDs – 2 Mb/s carriers	28	0.7	20	28	9.0	252	
MCDs – 6 Mb/s carriers	56	0.4	22	56	5.6	314	
Input processor	60	0.4	11	28	3.7	104	
Switch fabric & support	1	1.0	1	1	10.0	10	
Output processor	28	0.4	11	28	3.0	84	
Modulators	56	0.2	8	56	0.2	11	
Network Controller (ANC)	1	1.1	1	1	12.0	12	
Timing source	2	1.5	3	1	3.0	3	2–1 redundancy
DC/DC converter	2	7.0	14	1	83.4	83	90% efficiency
Structure	1	12.0	12				
Subtotals			104			874	

References

[1] *Radio Regulations Edition of 1990*, International Telecommunications Union, Geneva Switzerland, Revised March 1991.

[2] J. L. Harrold et al., "On-Board Switching and Processing", Proceedings of the IEEE, Vol. 78, No. 7, pp. 1206-1213, July 1990.

[3] M. G. Bellanger and J. L. Daguet, "TDM-FDM Transmultiplexer: Digital Polyphase and FFT", IEEE Transactions on Communications, Vol. COM-22, No. 9, pp. 1199-1205, September 1974.

[4] F. A. Tobagi, "Fast Packet Switch Architectures For Broadband Integrated Services Digital Networks", Proceedings of the IEEE, Vol. 78, No. 1, pp. 133-167, January 1990.

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[6] L. C. Palmer and L. W. White, "Demand Assignment in the ACTS LBR System", IEEE Transactions on Communications, Vol. 38, No. 5, pp. 684-692, May 1990.

[7] T. Kozaki et al., "32 X 32 Shared Buffer Type ATM Switch VLSI's for B-ISDNs", IEEE Journal on Selected Areas in Communications, Vol. 9, No. 8, pp. 1239-1247, October 1991.

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Chapter 5

Satellite Design

This chapter describes the satellite design needed to accommodate the Integrated Video payload. The resultant satellite's mass, power, and configuration are given. The chapter is organized as follows:

5.1 Introduction

The satellite design approach is given, the mass and power allocations are described, and the features of the satellite bus are summarized.

5.1.1 Satellite Design

The approach is to evolve the existing satellite design (1990 technology base for 1995 launch) to the Integrated Video satellite design which assumes a year 2000 technology base for a year 2005 launch. Table 5-1 compares the Integrated Video satellite design with those of three communications satellites currently being produced by Space Systems/Loral (formerly Ford Aerospace).

Superbird is a Japanese domestic communications satellite with X, Ku, and Ka-band transponders. Intelsat-7 is the next generation of international communications satellites and has C and Ku-band transponders. N-Star is a communications satellite being built for the Japanese telephone company NTT. These satellites are currently under production with launches scheduled in the 1992 to 1995 time frame.

In contrast, the Integrated Video satellite uses an onboard baseband switch that allows simultaneous interconnectivity between its 28 uplink and 28 downlink beams. NASA's ACTS satellite, planned for launch in 1993, will demonstrate the first generation of on-board switching. The combination of narrow spot beams and on-board switch to interconnect the beams according to traffic demands enables increased communications efficiency and thus increased capacity from the payload.

The payload mass fraction (ratio of the mass of the antenna plus communications electronics to the total satellite wet mass) is 20% for Superbird, 22% for Intelsat 7, and 27% for N-Star versus 31% for the Integrated Video satellite design. The improvement is due to technology advances in the propulsion and power subsystems. Ion propulsion is used to reduce the mass of on-orbit station-keeping fuel and thus enable longer lifetimes. Lower mass batteries and solar cells allow greater payload mass.

5.1.2 Satellite Mass and Power Allocations

The Integrated Video satellite design with 3,548 kg launch mass and 4.3 kW power is summarized in Table 5-1. Table 5-2 summarizes the satellite characteristics. An Atlas 2AS launch from the Eastern Test Range (ETR), i. e. Cape Kennedy, is assumed. Launching from the more equatorial site of French Guinea by the Ariane would reduce the satellite wet mass by 200 kg.

5.1.3 Summary of Satellite Design Features

The key features of the satellite design from the standpoint of the satellite bus are as follows:

Higher power is able to be supplied from the same size bus due to advanced battery and solar cell designs which have improved performance per unit mass.

Advanced nickel hydrogen batteries (NiH) are used which are based on estimates of battery performance and technology readiness dates by NASA/JPL [G. Halpert and A. Attia, *Advanced*

Table 5–1: Comparison of Integrated Video Satellite with Current Communication Satellites

Satellite Name	Superbird 1	Intelsat 7	N-Star	Integrated Video
Launch Year (first)	1992	1993	1995	2006
Launch Vehicle	Ariane 3	Atlas 2AS	Ariane 44P	Atlas 2AS
Lifetime (yr)	10	11	10 (12)	15
Number of satellites	2	5	2	–
Total Bandwidth, up/down (GHz)	1.8	2.4	2.6	4.0/7.5
Max. Capacity (Gb/s)	–	–	–	2.6
DC Power, end of life (kW)	3.55	3.53	4.1	4.3
RF Transmit Power (W)	885	929	1,050	637
Battery Capacity (W-hr)	3,964	3,972	4,592	5,660
Satellite Subsystem Mass (kg)				
Structure	208	209	200	210
Propulsion	91	108	112	281*
Power	174	180	188	132
Solar array	116	120	130	125
Attitude control	86	93	56	60
Spacecraft control electronics	–	80	74	60
TT&C	38	15	17	20
Thermal	93	94	103	120
Integration, elect. & mech.	114	105	131	130
Antenna	52	103	155	54
Communication electronics	246	320	370	535
Dry Mass of Satellite (kg)	1,218	1,427	1,536	1,727
On-orbit Fuel (kg)	273	454	422	160*
Wet Mass of Satellite (kg)	1,491	1,881	1,958	1,887
Orbit-raising Fuel (kg)	1,030	1,710	1,571	1,661
Launch Mass (kg)	2,521	3,591†	3,529	3,548†

† An equatorial launch (Ariane) would save 200 kg launch mass.
* Use of ion propulsion increases propulsion mass and decreases on-orbit fuel mass.

Table 5–2: Characteristics of Satellite to Supply Integrated Video Service

Manufacturer & model:	LORAL FS-1300
Baseline satellite name:	VideoSat
Lifetime:	15 yr
On-board switching:	Baseband switch interconnects channels.
Launch vehicle:	Atlas IIAS
Launch year:	2006
Frequency band and bandwidth:	Ka-band, 1,400 MHz
– receive:	27.5–30.0 GHz
– transmit:	18.3–20.2 GHz
Antenna	
– type:	Offset parabolic
– number:	2
– size:	0.8 m receive, 1.2 m transmit
– mass:	54 kg
– coverage (Ka-band):	28 fixed beams cover CONUS, both transmit & receive
Communications electronics	
– number of receivers:	28 at Ka-band.
– TWTAs:	49 @ 13 W
– mass:	535 kg
– dc power:	3,378 W
Spacecraft	
– size (stowed):	2.5 m x 1.88 m x 2.64 m
– mass, BOL:	1,887 kg
– power (EOL) at summer solstice:	4,318 W
– primary power:	Solar cells (thin silicon)
– batteries:	4 NiH, 240 Ah (total)
– attitude and station keeping:	3-axis stab, ion propulsion
– attitude pointing accuracy:	$\pm 0.05°$
– apogee motor:	Liquid propulsion
– stationkeeping & attitude control:	Ion propulsion motor

Electrochemical Concepts for NASA Applications, Proc. 24th IECE Conference, Aug. 1989, Vol. 3, Editor W. D. Jackson]. JPL concluded that advanced NiH batteries will be available in the year 2000 with 75 Wh/kg specific energy, compared to the capability of 1990 NiH batteries which provide 45 Wh/kg specific energy. We adopt a figure of 33 W/kg to estimate the power subsystem mass for our year 2006 satellites, based on their end-of-life DC power.

Thin silicon solar cells are used for the satellite designs. The assumed total array specific power is 35 W/kg (ratio of dc power to solar array mass). Thin silicon cells on a four panel, two wing configuration provide 5 kW power. This is the same configuration being qualified by Loral for Intelsat 7.

The Intelsat 7 design uses 8 mil (0.20 mm) thick cells. The assumption is made that by the year 2006, a 20% reduction in cell thickness can be made with the consequent 10% improvement in total array specific power since cell mass is 50% of array mass. An additional 5% radiation degradation is assumed for the extra 4 years of life. A specific power improvement of 10% over Intelsat 7 is achieved.

Thermal radiators are required to dissipate the higher power from the satellite. Of the 4.3 kW dc power, 0.7 kW is radiated away in rf power, leaving approximately 3.6 kW to be disposed of by the thermal subsystem.

Use of ion propulsion reduces the combined propulsion system plus on-orbit fuel mass. It becomes increasingly attractive as satellite lifetime is extended.

Orbit raising fuel has a higher specific thrust (320 vs. 310 ISP) and thus allows 50 kg more launch mass.

Use of Ka-band gives increased spectrum availability for communications, and a resultant higher communications capacity.

Multiple beam antennas are used rather than direct radiating phased arrays (or phased array feeds) on account of the multiple, simultaneous beams formed by each antenna. A design alternative would use phased arrays with scanning spot beams. Separate beam forming networks would be required for each of the 28 beams.

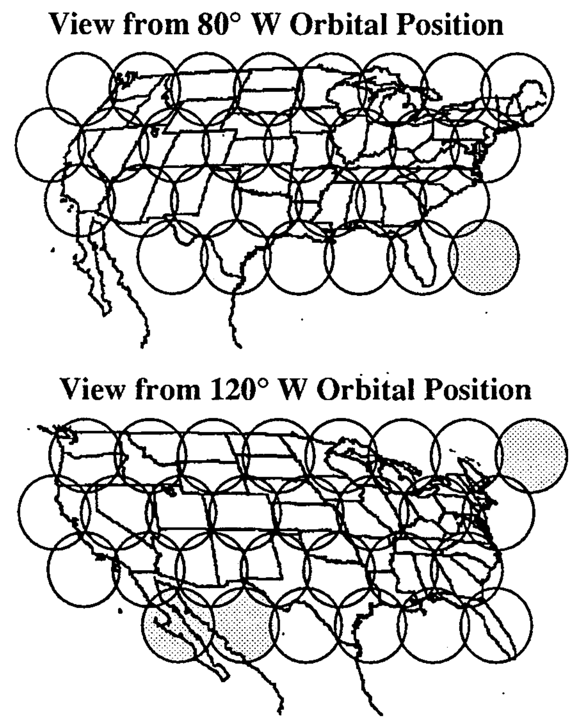

Figure 5–1: 28 Fixed Beams Cover CONUS

5.2 Integrated Video Satellite Design

This section describes the satellite design which is summarized in Table 5-2. This section is divided into four parts:

1. Antenna Coverage and Size
2. Payload Block Diagram
3. Payload Electronics Mass and Power
4. Satellite Characteristics

5.2.1 Antenna Coverage and Size

Figure 5-1 shows the antenna coverage for Architecture 1. Separate uplink and downlink multiple beam antennas supply 28 fixed beams of 0.87° diameter to cover the Continental United States (CONUS). The figure shows a total of 29 beam positions (horns), with the appropriate selection being made of the edge beams depending on the satellite's position in the geosynchronous arc.

There are two Ka-band multiple beam antennas:

- Ka-band receive (30 GHz) – 0.8 m, 24 kg mass.
- Ka-band transmit (20 GHz) – 1.2 m, 30 kg mass.

There are seven different beam frequencies, arranged in hexagonal groups of seven beams. The frequency band is reused 4 times over CONUS.

5.2.2 Payload Block Diagram

Figure 5-2 shows the payload block diagram. There are 28 input beams in seven groups of four; thus the LNAs and downconverters have 6-for-4 redundancy. Each input beam contains three channels at 36 Mb/s, one with 18 2-Mb/s carriers and the other two with 6 6-Mb/s carriers. The channels are separated by the input mux and passed to a multi-carrier demodulator (MCD). There are 28 2-Mb/s and 56 6-Mb/s MCDs of 36 Mb/s capacity, giving a total uplink capacity of 3.024 Gb/s. However, only 2.646 Gb/s can be used simultaneously since the downlink capacity is restricted to 2.646 Gb/s. However, the extra uplink capacity is useful in filling the satellite capacity, and allows flexibility in accommodating increased traffic from certain beams.

The baseband switch is serviced by 28 input and 28 output processors. The switch fabric is a TDM fiber optic bus with 3 Gb/s capacity. The total input capacity must be controlled not to exceed this capacity. This is achieved by controlling access to the system. It is envisioned that some beams will be at maximum capacity (108 Mb/s), while others are at a fraction of their capacity.

There are 28 output processors, each producing two 54-Mb/s data streams. One of the output data streams is always connected to the corresponding output beam. The other 54-Mb/s output is used when required for high traffic areas. Transmit power limitations give a maximum of 49 (out of a possible 56) 54-Mb/s output channels active at one time.

The output beams are also in seven groups of four, and the upconverters and TWTAs have 10-for-8 redundancy (actually less since only 49 of the 56 downlink channels are used at one time). There are 70 modulators, 70 upconverters, and 70 13-W TWTAs, only 49 of which are active at one time. An orthomode junction (OMJ) is used to transmit the second channel in a beam at a different polarization from the first beam. The OMJ has considerably less loss than an output multiplexer (0.2 dB versus 1.6 dB), and thus its use is preferred to save RF transmit power. The second channel in a beam can also be at a different frequency from the first channel to avoid rain depolarization problems, since there is adequate available bandwidth with this design. (In fact, there is sufficient bandwidth to use BPSK on the downlinks.)

5.2.3 Payload Electronics Mass and Power

Table 5-4 summarizes the payload electronics mass and power. Major components are as follows:

LNAs and downconverters have 6-for-4 redundancy. There are a total of 42 LNAs and 42 downconverters, with 28 of each active at one time.

MCDs (multi-channel demodulators) are the key component of the baseband processor in terms of mass and particularly power consumption.

TDM Fiber-Optic Bus switch supplies the simultaneous connectivity between the 28 inputs and 28 outputs.

Upconverters and TWTAs have 10-for-8 ring redundancy. There are a total of 70 upconverters and 70 TWTAs, with a maximum of 49 active at one time.

Also included in the mass and power tabulations of Table 5-4 are the coaxial and waveguide interconnections and the beacon transmitters for earth terminal pointing and rain fade detection. There is a provision for 5% payload mass and power margin.

The major payload items in terms of contribution to mass and power consumption are the 13 W TWTAs. Current technology is exemplified by the 29 W Superbird TWTA/EPC which has a mass of 3.5 kg and power efficiency of 30%. Assumption is made that another 10 years of development (year 2000 technology) will achieve a 13 W TWTA with 1.6 kg mass and 36% dc-to-rf efficiency (40% tube efficiency and 90% dc-to-dc efficiency). Use of MMIC components is assumed for electronic components where appropriate.

5.2.4 Satellite Characteristics

The bus design is based on the Loral FS-1300 series which has a 1,900 kg wet, beginning-of-life (BOL) mass capability and is presently in production for commercial applications such as Superbird, Intelsat-7, and

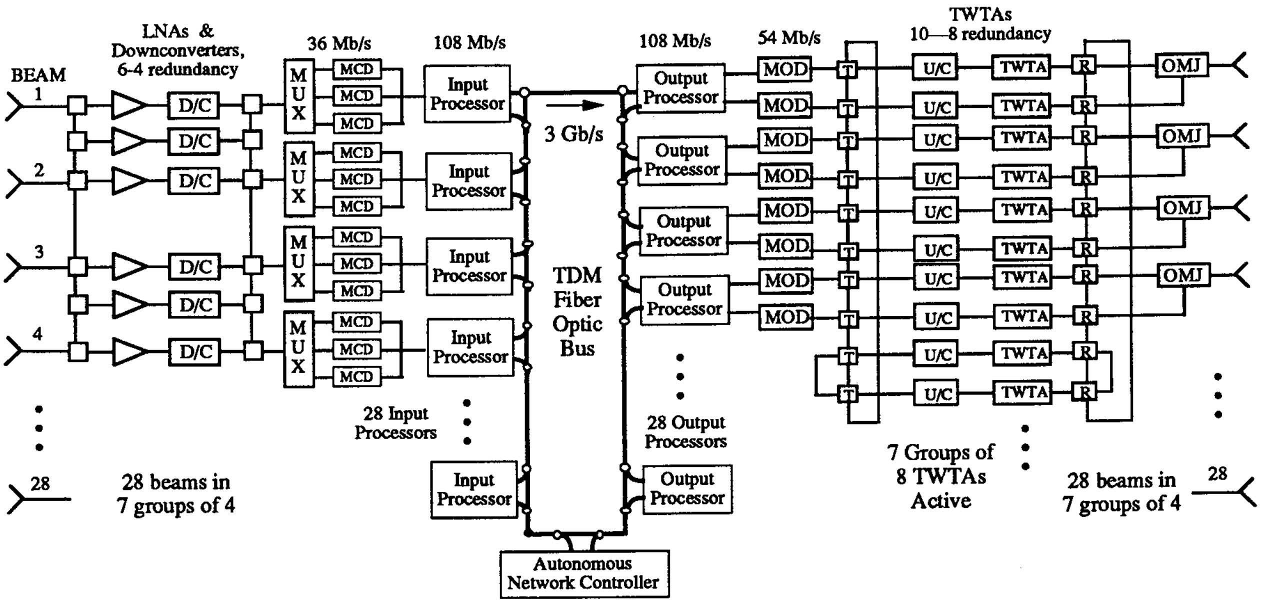

Figure 5–2: Payload Block Diagram

Table 5–3: Power Budget

Component	Power (W)	
LNAs, Receivers	258	
Transmitters	1,769	
Baseband electronics	874	
Other/Margin	477	
Total Payload	3,378	3,378
TT&C	30	
Attitude control	135	
Propulsion	12	
Power subsystem	52	
Thermal subsystem	163	
Control electronics	80	
Harness loss	44	
Total Bus	516	516
Battery charging		424
Total Satellite		4,318

N-Star. Table 5-2 summarizes the satellite characteristics. Figure 5-3 shows the satellite on-orbit configuration.

The existing satellite design (1990 technology) has been upgraded to incorporate hypothesized year 2000 technology improvements. The result is a 1,727 kg dry (1,887 kg wet) satellite mass with a 589 kg payload (antenna plus communication electronics) and 4.3 kW end-of-life power. Table 5-1 summarizes the mass budget by satellite subsystem. Table 5-3 gives the power budget for the satellite.

5.3 Discussion of Design

In spite of the addition of a 104-kg 874-W baseband processor and only 637 W of RF transmit power, the Integrated Video satellite has a total capacity of 2.646 Gb/s comprised of 504 2-Mb/s channels plus 273 6-Mb/s channels. In addition there is flexibility to simultaneously interconnect channels among beams in the point-to-point, multicast, or broadcast modes.

This performance is due to the following design factors:

- Regeneration on the satellite gives a 3-dB link performance advantage.
- Spot beams give more efficient use of satellite power.

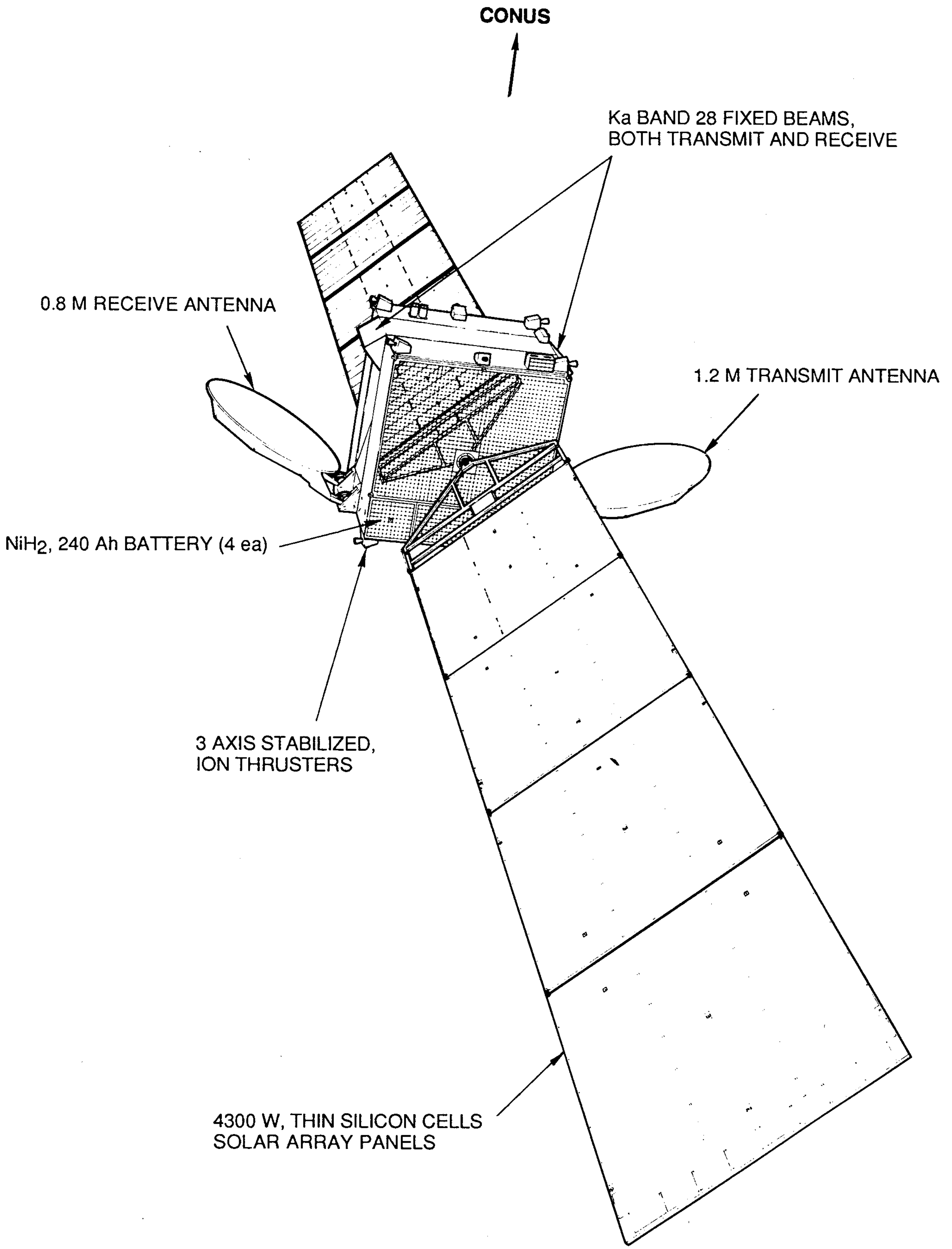

Figure 5–3: Integrated Video Satellite On-Orbit Configuration

Table 5–4: Payload Electronics Mass and Power Breakdown

Equipment	Mass (kg) Qty.	Mass (kg) Unit	Mass (kg) Total	Power (W) Qty.	Power (W) Unit	Power (W) Total	Comments
Baseband Processor							
MCDs – 2 Mb/s carriers	28	0.7	20	28	9.0	252	
MCDs – 6 Mb/s carriers	56	0.4	22	56	5.6	314	
Input processor	60	0.4	11	28	3.7	104	
Switch fabric & support	1	1.0	1	1	10.0	10	
Output processor	28	0.4	11	28	3.0	84	
Modulators	56	0.2	8	56	0.2	11	
Network Controller	1	1.1	1	1	12.0	12	
Timing source	2	1.5	3	1	3.0	3	2–1 redundancy
DC/DC converter	2	7.0	14	1	83.4	83	90% efficiency
Structure	1	12.0	12				
Subtotals			104			874	
Low noise amplifiers	42	0.4	26	28	1.2	34	6–4 redundancy
Receivers (28/4 GHz)	42	1.8	76	28	8.0	224	6–4 redundancy
Input demultiplexers	28	1.5	42				3 channel
Upconverter (4/20 GHz)	70	1.1	77	49	3.0	147	10–8 redundancy
TWTA/EPC (13 W, 20 GHz)	70	1.6	112	49	36.1	1,769	10–8 redundancy, 36% eff.
Output filter	56	0.2	11				
Master LO	2	5.0	10	1	6.0	6	2–1 redundancy
DC/DC convertor (upconverter)	35	0.4	14	25	6.0	150	2–1 redundancy
Redundancy switches			34				
Waveguide and coaxial cable			9				
Beacon transmitters	2	2.0	4	1	15.0	15	2–1 redundancy
Margin			25			159	5% margin
Totals			535			3,378	Mass (kg), Power (W)

- Convolutional coding on uplinks and downlinks gives 5 dB performance improvement.
- An OMJ for combining TDM downlinks in the same beam saves 1.5 dB compared to an output multiplexer.
- BPSK is used on downlinks, which saves 1.2 dB relative to QPSK due to less modem loss and co-channel interference loss.
- FDMA uplinks (and TDM/FDMA uplinks) give the additional advantage of allowing use of smaller earth terminals.

Chapter 6

User Costs

This chapter defines the overall system cost scenario; estimates the costs of the space segment, network control, and user ground terminals; and determines the composite pro rata user costs associated with various video communication services and capacity utilization. The chapter is organized as follows:

6.1 Cost Guidelines

6.2 Space Segment Costs

6.3 Ground Terminal Costs

6.4 Network Control Costs

6.5 Utilization Factors

6.6 Composite Costs

6.7 Discussion

6.1 Cost Guidelines

Cost guidelines are discussed in this section.

6.1.1 Key Technology Development Costs

The Integrated Video satellite incorporates advanced communications techniques including full demodulation, processing, switching and remodulation in the satellite. This is a major change from current transponder methods and significant R&D development will be required to assume satisfactory performance with high reliability.

The R&D effort would be incurred in the 1994 to 2002 time period, assuming space segment hardware contract in year 2002 with first launch in year 2006. The costing estimates assume that such developments would be separately funded by NASA R&D programs.

6.1.2 Space Segment Cost Guidelines

The key elements of the space segment would consist of the following:

- Development and manufacture of two satellites with contract award in year 2002.
- Launch of two satellites in 2006.
- TT&C control of satellites over a 15 year period.
- Each satellite has a 15-year on-orbit life.

6.1.3 User Terminal Cost Guidelines

The costs associated with the user terminals would include the terminal lease and associated repairs and maintenance costs over a 15 year period. It is assumed that a terminal may be upgraded during the 15 year operations period but that a full replacement terminal would not be required. No salvage value of the terminal equipment is assumed at the end of the 15 year period.

It is postulated that the various Ka-band terminals would be manufactured in large quantities in support of this as well as other programs. The quantities would be tens of units for the network control terminals (5 m) and hundreds or thousands of Integrated Video user terminals (1.2 m, 1.8 m, and 3 m).

The costs associated with acquisition of land and/or buildings for the terminal site and the costs of associated with the terminal operations room or with operations personnel are not included.

6.1.4 Network Control Center Cost Guidelines

It is postulated that a single communications control center, located within CONUS, would be used to control access to the Integrated Video communications subsystem. The antenna system would operate at Ka-band.

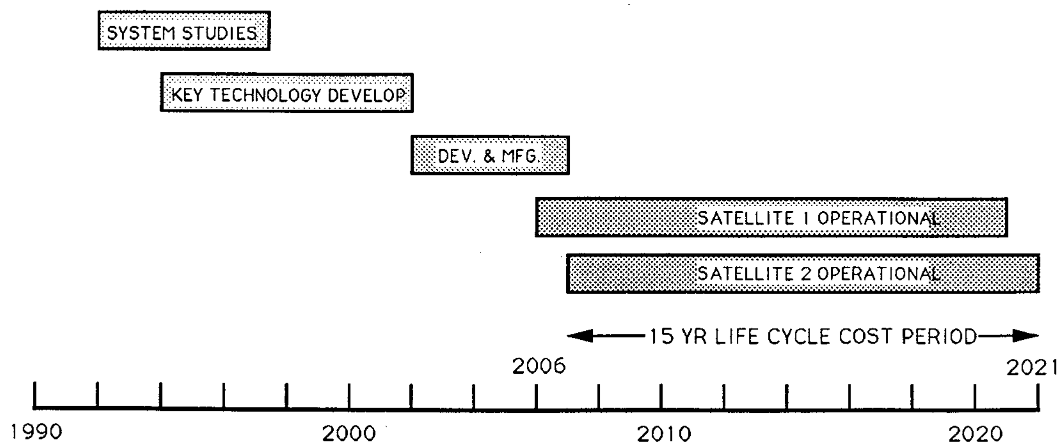

Figure 6–1: Schedule for Integrated Video Satellite System Implementation

For improved performance and availability during severe rainfall periods, three separate terminals would be located several kilometers apart to provide site diversity.

6.1.5 System Utilization Cost Guidelines

The degree of composite users utilization of available system capacity over time has a very significant impact on allocation of space segment costs per unit of information transmittal. The model for capacity usage is postulated as follows:

- The theoretical maximum capacity is 2.646 Gb/s for a single satellite (downlink limited).
- The system achieves 10% to 20% utilization.

6.1.6 Program Schedule

A summary of schedule planning for system implementation is shown in Figure 6-1. The plan calls for manufacturing to begin in 2002 with two launches in 2006.

6.2 Space Segment Costs

For this study the space segment costs comprise the total of development and manufacture of two satellites, launch of two satellites, insurance, and TT&C support. The space segment cost discussion is divided into five parts; (1) satellite costs, (2) launch costs, (3) insurance cost, (4) TT&C costs, and (5) total space segment costs.

Table 6–1: Satellite Launch Cost ($M, 1992)

Category	Cost
Hardware	$85 M
Launch Support	12 M
Integration	12 M
Other	15 M
Total (1 sat.)	$124 M

6.2.1 Satellite Costs

Satellite costs are extrapolations from those for the current communications satellite programs of Space Systems/Loral, according to subsystem mass. Cost categories include bus subsystems, communications payload, integration and assembly, ground equipment, and program management.

Table 6-2 summarizes these costs which include a 10% fee to the satellite manufacturer. A commercial program is assumed. (A government (NASA) satellite program would have 40% higher nonrecurring costs and 15% higher recurring costs due to additional testing, monitoring, and paperwork requirements.)

The estimated cost for an Integrated Video satellite is $280 M (Table 6-2), which compares with a price $140 M for the current Intelsat VII satellites which are of comparable size (see Table 5-1). The difference in cost is primarily due to the larger (535 kg vs. 320 kg) and more complex payload.

Table 6–2: Cost for Development and Manufacture of Two Satellites

	Costs, $M (1992)		
Cost Category	Non-Recurring	Recurring (2 sats.)	Total
Satellite Bus	70.4	110.5	180.9
Communications Payload	15.4	67.1	82.4
Integration & Assembly	6.5	15.7	22.3
Ground Equipment	15.1	–	15.1
Program Management	33.5	75.2	108.7
Cost Subtotal	140.9	268.5	409.4
Payload Complexity Factor	50	50	100
Fee at 10%	19.1	31.8	50.9
Total Cost	210.0	350.4	560.3

6.2.2 Launch Costs

The expected launch vehicle for year 2006 launch of the Integrated Video satellites would be the Atlas IIAS which has planned capacity of 3,600 kg to geosynchronous transfer orbit (GTO). The price per launch, assuming two launches, is given in Table 6-1. The launch support costs include mission operations and TT&C support for the launch.

6.2.3 Insurance Costs

A launch insurance rate of 16% of the total launch value is assumed. It is expected that the rate will be in the range of 15% to 20% of costs insured and would be dependent upon the maturity and launch success record of the Atlas IIAS launch vehicles.

6.2.4 TT&C Costs

The costs of TT&C associated with the initial launch are included in the launch cost segment. It is expected that standard TT&C hardware would be used and that no unique TT&C facility would be required. It is estimated that TT&C services could be obtained at a yearly cost of $1 M for two satellites.

6.2.5 Total Space Segment Costs

A summary of annual program costs for the Integrated Video satellites is given in Table 6-3. The annual cost based on an 18% rate of return is also given. The life cycle cost is $490 M per satellite or $96 M per satellite per year over a 15 year period beginning in the year 2006.

The maximum satellite capacity is 504 2-Mb/s circuits and 273 6-Mb/s circuits, a total capacity of 2.646 Gb/s. The system is downlink limited, the uplink capacity is slightly higher at 3 Gb/s.

6.3 Ground Terminal Costs

Several Ka-band ground terminal configurations are used, ranging in size from 1.2, 1.8, and 3 m for user terminals, and 5 m for the large network control terminals. The total ground terminal costs include initial terminal acquisition (or annual lease cost), maintenance and repair costs, and periodic upgrade and maintenance costs. Additional costs include installation and checkout, onsite costs, and operator personnel costs.

6.3.1 User Terminal Costs

The user terminal sizes are 1.2, 1.8 and 3 m with respective transmit powers of 4, 10, and 20 W at Ka-band (4 W amplifiers should be available in solid state). Uplink data rates are 2 or 6 Mb/s for a single video transmission.

The different combinations of terminal size and transmit power give different availabilities as shown in Table 6-4. D-QPSK and a rate 1/2 Viterbi code are used for the 2 Mb/s and 6 Mb/s uplinks, and the transmitter and receiver are tunable to different frequency bands.

Table 6–3: Space Segment Costs, 1992 $M (2 satellites, 15 yr life beginning 2006)

Cost Category (2 satellites on orbit)	Life Cycle Cost	Annual Cost at 18%
Satellite cost (2)	560 M	
Launch Cost (2)	248 M	
TT&C Support (2)	15 M	
Launch Insurance (16%)	157 M	
Total Costs	$980 M	$192 M/yr

The TDM 54-Mb/s downlinks use BPSK modulation and rate 1/2 Viterbi coding.

Manufacturing quantity is expected to be 1,000 for the 3-m terminals, 3,000 for the 1.8-m terminals, and 6,000 for the small 1.2-m terminals. The two satellite system has 1,008 2-Mb/s circuits and 546 6-Mb/s circuits. Thus the assumed ratio of users to circuits is approximately 6-to-1 for the 1.2-m 2-Mb/s users and 7-to-1 for the 1.8-m and 3-m 6-Mb/s users.

Users in high rainfall regions or with high availability requirements may elect larger diameter antennas or higher power amplifiers than users of the same communications services in low rainfall regions.

Significant items contributing to user terminal costs are the high power amplifiers and modems. Table 6-4 estimates user costs for 1.2, 1.8, and 3 m terminals. The 1.2-m, 2-Mb/s terminal has a lower cost because of its smaller size, lower transmit power, and greater production quantity which allows a reduction in non-recurring cost allocation and increased manufacturing efficiencies.

A codec, which costs $80 K today and is estimated to cost $20 K in the future, is also required for video transmissions. However, it is not included as part of the user terminal cost since codecs are required for all video transmissions, not just those going via satellite.

6.3.2 Network Control Terminal Costs

The network control terminal cost breakdown is given in Table 6-4. Although of larger size than the user terminals, many of its components such as modems and codecs are the same as in the smaller user terminals.

6.3.3 Terminal Sharing Concepts

The advent of wideband local area networks will make it possible for multiple users to share a common user terminal providing that available capacity is not exceeded. For example multiple buildings at a university or multiple companies in a town could share a common terminal, thus reducing the cost per user by increasing the utilization of the terminal.

Sharing becomes very favorable statistically if, for example, 30 circuits are shared by 60 users who only use their circuit half the time. The user circuit cost can be cut in half with only the penalty of an occasional wait for a free circuit.

There is even more to be gained from terminal sharing if links are asymmetric, i. e. users are either transmitting or receiving but not both equally at the same time. Then a mostly "receiving" user can use the terminal at the same time as a mostly "transmit" user.

6.3.4 Terminal Lease Fees

The initial capital expenditures may be reduced by leasing of terminals. Table 6-5 estimates terminal costs and gives the yearly lease fee assuming 20% of the terminal acquisition cost per year over 15 years for debt servicing and profit. This is equivalent to 18% return on investment for the leasing company. An additional yearly cost for maintenance and periodic upgrade of terminal subsystems typically equals 10% of the initial acquisition cost, with no value included for operating personnel.

Table 6-6 gives the terminal cost per minute of operation, assuming different amounts of usage per working day. (We postulate five working days per week and 250 working days per year). Costs range from a few cents per minute of use 24 hours per day to several dollars per minute for use of 1 hour per day. It is clear that the

Table 6–4: Ground Terminal Costs (1992 $M)

	Small User Terminal	Medium User Terminal	Large User Terminal	Network Control Terminal
Terminal Parameters				
Size	1.2 m	1.8 m	3 m	5 m
Transmit Power	4 W	10 W	20 W	50 W
Total Number of Terminals	6,000	3,000	1,000	4
Data Rate: Uplink	2 Mb/s	6 Mb/s	6 Mb/s	6 Mb/s
Downlink	54 Mb/s	54 Mb/s	54 Mb/s	54 Mb/s
Access Scheme: Uplink	FDMA	FDMA	FDMA	FDMA
Downlink	TDM	TDM	TDM	TDM
Modulation, Uplink	D-QPSK	D-QPSK	D-QPSK	D-QPSK
Downlink	BPSK	BPSK	BPSK	BPSK
Coding (up/down)	Viterbi	Viterbi	Viterbi	Viterbi
Availability (Region E)	98%	99%	99.5%	99.8%
Non-recurring Costs				
Management and system design	$1,000	$2,000	$3,000	$20,000
Equipment design	$2,000	$4,000	$5,000	$50,000
Recurring Costs				
Production management	$1,000	$1,000	$2,000	$20,000
Antenna subsystem	$4,000	$6,000	$8,000	$20,000
Electronics, antenna mounted	$9,000	$12,000	$15,000	$25,000
Electronics, control room	$11,000	$13,000	$13,000	$30,000
Integration hardware	$3,000	$3,000	$4,000	$7,000
Assembly and test	$4,000	$4,000	$5,000	$8,000
Total Costs	$35,000	$45,000	$55,000	$180,000

Table 6–5: Ground Terminal Annual Costs (1992 $)

Terminal Type and Cost	Lease Cost ($/yr)	Maintenance Cost ($/yr)	Total Cost ($/yr)
Small (1.2 m), $35,000	7,000	3,500	10,500
Medium (1.8 m), $45,000	9,000	4,500	13,500
Large (3 m), $55,000	11,000	5,500	16,500

Table 6–6: Ground Terminal Costs per Minute vs. Number of Hours Utilized per Working Day

		Terminal Cost, $/minute of Use					
	Annual Cost	Number of hours utilized per working day					
Terminal Type	($/yr)	1	2	4	8	12	24
Small (1.2 m)	10,500	0.70	0.35	0.18	0.09	0.06	0.03
Medium (1.8 m)	13,500	0.90	0.45	0.23	0.11	0.08	0.04
Large (3 m)	16,500	1.10	0.55	0.28	0.14	0.09	0.05

amount of utilization has a large effect on prorata terminal costs, and thus schemes which share a terminal among users are economically attractive.

6.4 Network Control Costs

The regular on-orbit housekeeping functions for monitoring and care of Integrated Video satellite subsystems are achieved by the TT&C subsystem with costs defined as part of the space segment.

The communications access control to the satellite is performed by a single communications network control center located within CONUS. Users would request data channels and capacity through this facility. The cost for development and construction of this control center is estimated to be $100 M stated in 1992 dollars. This is equivalent to a cost of $20 M/yr for 15 years at 18% rate of return. The control center facility is forecast to have yearly maintenance and operating costs of about $4 M based upon a level of 10 people (see Table 6-7).

6.5 Capacity Utilization

The theoretical "maximum capacity" of a single satellite is 2.646 Gb/s of simplex circuits (maximum downlink capacity). This consists of 504 2-Mb/s circuits and 273 6-Mb/s circuits. However, average capacity utilization will be considerably less due to a number of factors.

- Varying distribution of users among a discrete number of satellite antenna coverage beams.
- Inefficient allocation of channels among a discrete number of multichannel demodulators which are of two types, 2 Mb/s and 6 Mb/s.
- Inefficient allocation of capacity within channels for TDMA sharing of uplink channels.
- The average utilization is reduced from peak use because of daily and hourly variations in user communication needs.
- Capacity is reduced by the frame overhead, estimated at 85% efficiency for the uplink and 95% efficiency for the downlink (see ¶4.8).

The average utilization of capacity is estimated to be around 15% of the peak utilization. This is equivalent to use of the full satellite capacity 5.2 hours per day, 250 days per year.

Table 6–7: Space Segment and Control Costs

	Annual Cost
Space Segment Charges	$192 M
Network Control Center Charges:	
Development and Manufacture	$20 M
Operations (15 yr)	$4 M
Total Yearly Charges ($ 1992)	$216 M

Table 6–8: Space/Control Costs vs. Circuit Size

Circuit Size	Simplex Circuit Cost ($/min) for System Utilization of 10%	15%	20%
64 kb/s	0.05	.033	0.025
128 kb/s	0.10	0.07	0.05
256 kb/s	0.20	0.13	0.10
512 kb/s	0.39	0.26	0.20
1 Mb/s	0.79	0.53	0.39
2 Mb/s	1.58	1.05	0.79
6 Mb/s	4.74	3.16	2.37

6.6 Composite Costs

Total user costs are derived by a two step process. First the space segment and network control costs for a simplex circuit are derived. Second, the user terminal costs are added to the space/control costs to obtain the total user cost per minute of circuit use.

6.6.1 Space/Control Costs for Simplex Circuit

Table 6-7 gives the total yearly costs for the space segment and network control for two satellites, assuming a 15 year life starting in the year 2006. The annual cost is $216 M for 5.3 Gb/s maximum capacity (2 satellites). Additional costs are incurred for the user ground terminal.

Table 6-8 gives the space/control cost per simplex circuit minute as a function of satellite utilization. At 100% utilization, the cost is $77.50 per minute per Gb/s simplex circuit capacity. For utilization of 15%, cost is $517/min per Gb/s, or $8.62 to transmit 1 Gb (see Appendix C, Table C-5).

The Integrated Video system (2 satellites) has 1,008 2-Mb/s circuits and 546 6-Mb/s circuits. However, TDMA can be used on the uplink to allow a number of smaller users to share a single circuit in time. Thus Table 6-8 gives simplex circuit costs for 64 kb/s, 128 kb/s, 256 kb/s, 512 kb/s, and 1 Mb/s circuits as well as the 2 Mb/s and 6 Mb/s circuits. Circuit costs are given for system utilizations of 10%, 15% and 20%.

6.6.2 Total User Costs per Circuit Minute

Tables 6-9, 6-10, and 6-11 give total costs for the 1.2 m, 1.8 m, and 3 m terminal users respectively for 15% system utilization. The space/control segment cost is added to the ground terminal cost in order to obtain the total user cost.

Total user costs are given for different data rates and hours/day use of the ground terminal. The tables give the simplex (one-way) circuit cost plus one ground terminal cost. A duplex circuit (two-way) and two ground terminals would cost double the value in these tables. There is not simultaneous sharing of ground terminal capacity (i. e., a user smaller than 2 Mb/s pays the full price of the ground terminal).

There are several points that must be made regarding these tables:

- Tabulated total cost is the sum of the space segment/control cost (Table 6-8) and the ground terminal cost (Table 6-6). Depending on circuit size and ground terminal cost and usage, the space or ground costs can dominate.
- User costs are a strong function of selected data rate for the larger size circuits where the space segment costs are larger than the ground terminal costs. This is also true if the terminal utilization is high (many hours per day).
- If terminal utilization is low, the total user cost changes very little with data rate. This is because the ground terminal costs are much larger than the space segment costs.
- The establishment of a duplex circuit will double the simplex circuit cost shown in the tables.
- The costs will vary directly according to changes in the overall system utilization factor which is assumed to be 15% in these tables. Thus there will incentives for the system operator to sell off-peak capacity at lower rates in order to increase utilization.
- For circuit sizes smaller than 2 Mb/s where TDMA sharing of the channel is assumed, the full cost of the ground terminal is assumed to be born by the single user. If other users are simultaneously sharing the terminal, the actual user charges will be lower due to prorata allocation of costs.

It must be emphasized that the user is only charged for the communications capacity used, i. e. the actual bits transmitted. Circuit establishment and disconnection, or reconfiguration to a new size can be accomplished in a few seconds.

The circuit costs of Table 6-9 can be divided by the circuit size to obtain a cost to transmit a given amount of information. The below tabulation gives the cost and time to transmit 1 Gb of information from the three different user classes (small 1.2 m at 2 Mb/s, medium 1.8 m at 6 Mb/s, and large 3 m at 6 Mb/s). System utilization is assumed to be 15% (same as Tables 6-9, 6-10, and 6-11). Terminal use is assumed to be 8 hours per day. The full cost of one ground terminal is included.

User Type	Terminal Size	1 Gb Transmit Cost	1 Gb Transmit Time
Small	1.2 m	$10.25	500 sec
Medium	1.8 m	$9.42	167 sec
Large	3.0 m	$9.56	167 sec

As a point of reference, this report contains about 1 Mb of text and graphic information. A digitized TV picture (1 frame) could contain 100 Mb; thus 1 Gb is equivalent to 10 color video pictures (uncompressed). A 5 minute "videophone" call at 128 kb/s (two-way) would takes 0.08 Gb. However, a 1-hour video conference between two locations at 6 Mb/s would take 43 Gb.

6.7 Discussion

Table 6-12 summarizes the data of Tables 6-9, 6-10, and 6-11 for simplex circuit costs. Overall system utilization is assumed to be 15%. It is assumed that the 2-Mb/s channel in a 6-Mb/s terminal (1.8 m or 3 m) bears the full cost of the terminal during use, even though three 2-Mb/s users could simultaneously share the 6-Mb/s terminal (i. e., unshared terminals).

Costs are now calculated for duplex circuits. (Note that previous work was for simplex circuits defined as one-way transmission plus full cost of one ground terminal.) Assume 15% system utilization as in the pre-

Table 6–9: Total Cost for Small Terminal User (1.2 m, 98% Availability)

Terminal Use (hr/day)	Total User Costs ($/min), Simplex Circuit for Data Rate (Mb/s)						
	0.064	0.128	0.256	0.512	1.0	2.0	6.0
1	0.73	0.77	0.83	0.96	1.23	1.75	–
2	0.38	0.42	0.48	0.61	0.86	1.40	–
4	0.21	0.25	0.31	0.44	0.71	1.23	–
8	0.12	0.16	0.21	0.35	0.62	1.14	–

Table 6–10: Total Cost for Medium Terminal User (1.8 m, 99% Availability)

Terminal Use (hr/day)	Total User Cost ($/min), Simplex Circuit for Data Rate (Mb/s)						
	0.064	0.128	0.256	0.512	1.0	2.0	6.0
1	0.93	0.97	1.03	1.16	1.43	1.95	4.06
2	0.48	0.52	0.58	0.71	0.98	1.50	3.61
4	0.26	0.30	0.33	0.49	0.76	1.28	3.39
8	0.14	0.18	0.24	0.37	0.64	1.16	3.27

Table 6–11: Total Cost for Large Terminal User (3 m, 99.5% Availability)

Terminal Use (hr/day)	Total User Cost ($/min), Simplex Circuit for Data Rate (Mb/s)						
	0.064	0.128	0.256	0.512	1.0	2.0	6.0
1	1.13	1.17	1.23	1.36	1.63	2.15	4.26
2	0.58	0.62	0.68	0.81	1.08	1.60	3.71
4	0.31	0.35	0.41	0.54	0.81	1.33	3.44
8	0.17	0.21	0.27	0.40	0.67	1.19	3.30

Table 6–12: User Cost ($/min) for Simplex Circuits

Ground Terminal			Cost for rate (Mb/s)	
Size	Avail-ability	Use (hr/day)	2.0	6.0
1.2 m	98.0%	1	1.75	–
1.8 m	99.0%	1	1.95	4.06
3.0 m	99.5%	1	2.15	4.26
1.2 m	98.0%	2	1.40	–
1.8 m	99.0%	2	1.50	3.61
3.0 m	99.5%	2	1.60	3.71
1.2 m	98.0%	4	1.23	–
1.8 m	99.0%	4	1.28	3.39
3.0 m	99.5%	4	1.33	3.44
1.2 m	98.0%	8	1.14	–
1.8 m	99.0%	8	1.16	3.27
3.0 m	99.5%	8	1.19	3.30

Table 6–13: User Costs for Duplex Circuits

User Size (m)	Total User Costs ($/min), Duplex Circuit for Data Rate (Mb/s) 0.128	0.256	0.512	1.0	2.0	6.0
1.2	0.50	0.62	0.88	1.42	2.46	–
1.8	0.60	0.66	0.98	1.52	2.56	6.78
3.0	0.70	0.82	1.04	1.62	2.66	6.88

vious tables and 4 hour per working day terminal utilization.

Table 6-13 gives the duplex circuit cost for different circuit sizes for the small (1.2 m), medium (1.8 m), and large (3 m) users. A 5 minute "videophone" duplex call at 128 kb/s (two-way) between two small users would cost $2.50.

A 1-hour video conference between two large users at 6 Mb/s would cost $396 (requires 4 simplex half circuits where a half circuit is from the ground to the satellite or vice versa). A 1-hour video conference between three locations for large users at 6 Mb/s would cost $891 (requires 9 simplex half circuits). However, 1-hour video conference between four locations for large users at 6 Mb/s would cost $1,584 (requires 16 simplex half circuits).

Appendix C presents a cost comparison between the Integrated Video satellite system and two other concepts, the B-ISDN and Mesh VSAT systems.

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Chapter 7

Critical Technologies

This chapter identifies and describes the necessary technologies which are critical or enabling to the application of satellite delivered Integrated Video service. Also provided are plans for the development of such technology, including schedules and costs. This chapter is organized as follows:

7.1 Identification of Technologies

7.1.1 Hardware Development

Polyphase multiple carrier demodulators (MCDs) operate with uniform carriers (either at 2 or 6 Mb/s) over a 36 MHz band. The power consumption of each MCD is targeted to be less than 10 W.

FEC decoders operate at 100 Mb/s, using Rate 1/2 convolutional code with a 16 state code. The coding gain is expected to be 5.4 dB at an BER of 10^{-6}.

GaAs digital devices for fiber-optic interfaces with a speed of 400 Mb/s and a power consumption about 0.05 mW/gate.

7.1.2 Systems Engineering Development

Bit synchronous TDMA system. The MCD design has less mass and power consumption with a bit synchronous system. A study of feasibility, design approach, performance assessment via computer simulation, and cost-benefit tradeoff is required. This study must occur before the MCD development is started.

Design of the signaling packet for transmit acquisition. To determine the exact format and size of the signaling packet assuming that the guard time between TDMA frames is 60 μs and the timing acquisition window is 170 μs.

On-board network controller with a flexible strategy. The network controller must be fast and flexible enough in changing multipoint connections, service quality, and channel bandwidth.

Rain fade mitigation technique.
Effective techniques must be developed to combat excessive propagation loss by a combination of resource allocation methods through an increase of EIRP, a decrease of information bit rate, and/or the inclusion of a special FEC codec in the affected transmission channel.

7.2 Technology Development Plan

The Technology Development plan as part of the Integrated Video Satellite Program is given in Table 7-1. The following steps are assumed:

- The procurement cycle of Integrated Video satellites will begin in the third quarter of 1999 by issuing a draft satellite specification to the Industry for comments.
- The issuance of RFP in the year 2000.
- The selection of spacecraft contractors in 2001.
- The launch of the first satellite with the commencement of B-ISDN network operation by early 2006. (The schedule is shown in Figure 6-1, Chapter 6.)

Table 7–1: Technology Development Plan

Item	Start	Finish
Integrated Specifications	3/95	1/96
Services		
Traffic		
Performance		
Quality of Service		
Draft System Engineering Specifications	3/95	1/96
Space segment		
Ground segment		
Network management & control		
Critical Technology Development		
Bit synchronous system	1/94	1/95
Polyphase MCDs	1/96	9/98
FEC decoders	1/96	9/98
GaAs digital devices	9/96	1/98
Signaling packet design	9/96	1/98
On-board network control strategy	9/96	1/98
Rain fade mitigation techniques	9/96	1/98
Final Systems Engineering Specifications		6/99
Issuance of Draft Procurement Specification		9/99
Receive Comments from Industry		1/00
Issuance of Draft Procurement Specification		9/00
Procurement Cycle	1/01	9/01
Launch and Begin Operations		1/06

Appendix A

Video Practices

A.1 TV Transmission Categories

Table A-1 compares a number of television transmission systems that have been used with satellites, cable, and digital transmission links. Theses are rated generally by decreasing quality, and by decreasing requirements for transmission bandwidth.

Table A-1 TV Processing and Service Categories

QUALITY	TECHNIQUE	#/XPDR	RESOLUTION	SNR	ARTIFACTS
Studio	30 MHz FM	1	Full (640 x 480)	56	N/A
	45 Mb/s digital	1	Full	56	Barely Perceptible
	TMVT FM	2	Full	56	Barely Perceptible
	B-MAC FM	1	Full	56	N/A
Broadcast	Half Xpdr	2	Full	51	N/A
	B-MAC FM	2	Full	51	N/A
	TMVT FM	3	Full	51	N/A
Cable	15 Mb/s Sony SNG	2	Slightly Reduced	45	Perceptible
	7.5 Mb/s Digicipher	4	Slightly Reduced	45	Perceptible
DBS	3 Mb/s Skypix	4-18	480 x 386	42	Very Noticeable
	3 Mb/s Digicipher	10	280 Lines	42	Very Noticeable
VCR	Analog	N/A	2.5 MHz, 280 Lines	42	N/A
Teleconference	1.544 Mb/s				Limited Motion
	384 kb/s (H.261)		varies (352 x 288)		Limited Motion
	56-64 kb/s		varies (256 x 240)		Very Limited Motion

Studio quality is required for signals used for program production. It is used in links between network production centers, where program segments from several sources are combined to make the final program. Requirements are stringent because of the multiple generations of copies needed in the production phase. This is still the quality requested for programs that may be used for multiple broadcasts.

Broadcast quality is used in two areas. Electronic news gathering (ENG) has exploded. At one time, most news was first generated in a film camera (often 16 mm), that was then edited and finally distributed either live, or to a recorder for later use. The other is for program distribution to affiliates to cable head-ends where no additional editing or production work will be needed.

The cable category is used to define systems providing quality equivalent to that currently found in cable systems. While the current cable channels are similar to those in broadcasting, the quality of the received program is determined in part by the received signal strength and in reflections. The two systems that are listed are evolving standards that may eventually be used in conjunction with other networks for program distribution using cable.

DBS (Direct Broadcast Satellite) equipment is being proposed for use in a direct broadcast system to complement cable TV, or to extend the availability of television channels to areas not currently being served by cable. Although some of the advertising claims "high quality", these systems currently deliver signals that are of much lower quality than currently found in the Studio and Broadcast classes.

VCR (Video Cassette Recorders) require special formats to record on tape using analog techniques. The luminance and chrominance are carried separately. The luminance channel is placed on a carrier since tape cannot record some of the low frequencies.

Teleconference codecs are designed to operate in rates from the 64 kb/s ISDN B channel to a T1 or primary rate ISDN channel. These codecs perform extensive processing of the signal, and are intended primarily to display a head-and-shoulders view of one person, or of a small group of people. The quality required of this equipment is much lower than most the other groups, but so are the transmission requirements. The codecs in this class originally cost nearly $200,000 but newer equipment is now available for less than 10% of this cost.

Digital video codecs exist primarily in two groups: ones at D3-D4 levels (32 Mb/s to 140 Mb/s) and D1 levels (64K to 2 Mb/s). The 45 Mb/s codec in the table can be transmitted using D3 rate facilities found in North America. The D3 codecs provide quality that approaches broadcast quality and codec prices are relatively low, but the cost of transmission is a barrier to widespread use. The D1 codecs have seen the largest use, and are expected to continue to have a high growth rate. The focus of section is primarily video codecs operating at rates below 2 Mb/s.

A.2 Television Standards

Standard television cameras and monitors are the video source and display for most videoconference systems. Videoconference systems are usually designed to be compatible with one of these systems so that low cost cameras, studio equipment, and video displays can be used. Codecs are employed to reduce the amount of bandwidth required for transmission.

Four parameters for television images are the number of lines in a complete picture, the number of fields per second, the number of fields in a picture, and the ratio of the width to height of the picture (aspect ratio). In general, television images are designed to display equal resolution in the horizontal and vertical direction. Temporal resolution is determined by the field and frame rate. The critical viewing distance for a television picture is the distance where the distance between scan lines is equal to the limit of visual acuity of the eye. This is the distance where the individual scan lines are just perceptible. Figure A-1 shows relative sizes of television standards at the critical viewing distance.

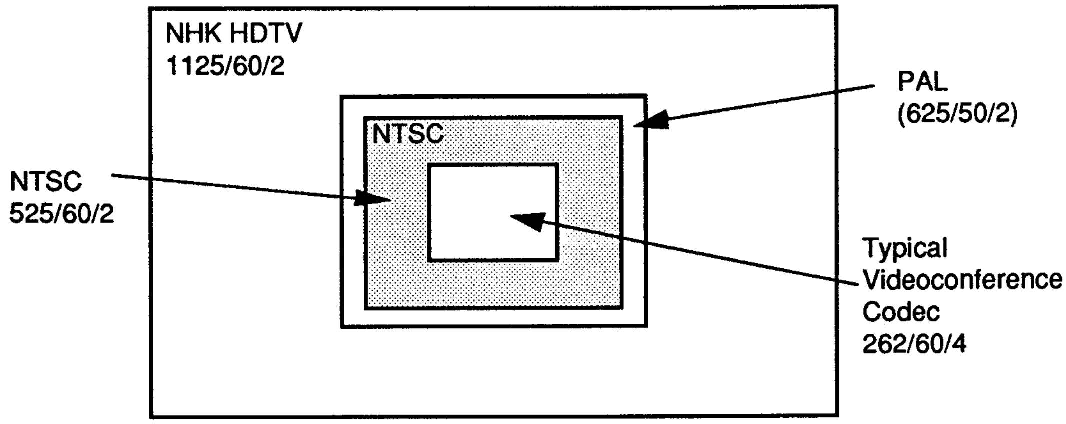


Figure A-1 Television Formats Viewed at Critical Distance

The critical viewing distance is often described by the ratio of the viewing distance divided by the picture height. Television images are described by the diagonal dimension of the display. For NTSC the aspect ratio is 4:3, and the picture height is approximately 0.6 of the diagonal. Therefore, the height of a 20 inch monitor is approximately 12 inches. The critical viewing distance is between 4 and 6 times the height, or 4 to 6 feet. Moving closer simply makes the scan lines become more visible. For larger distances, fine detail becomes less visible.

A.2.1 NTSC (also includes comparison to PAL, SECAM)

Three color television systems have become wide spread standards throughout the world since the mid 1950's. The first was NTSC (National Television Standards Committee) and was approved by the FCC. This was a 525 line signal, 29.97 Hz frame rate with 2:1 interlace, and a compatible color subcarrier using AM modulation. The color television signal was compatible with existing black and white sets, and used the same TV bands that had been previously used for monochrome transmission.

During the time that the FCC was sponsoring tests, work was also being performed in Europe. The two standards that evolved used 625 lines, a 25 Hz frame rate with 2:1 interlace, and a compatible color subcarrier. One system, PAL (Phase Alternate Line) used a color subcarrier similar to the NTSC carrier. The other, SECAM, used FM modulation for the subcarrier. Other standards also exist, with line rates to 819 lines.

One difficulty with the existence of three standards is the interworking with other countries. Specialized (and expensive) equipment was used for a number of years between North America and Europe. Today, digital technology and signal processing chips have made standards conversion equipment much more affordable, and it is included in some products for a modest increase in cost.

A.2.2 HDTV

HDTV (High Definition Television) at one time was a defacto standard based on a system developed and promoted by Japan. This system uses 1125 lines, 5:3 aspect ratio, and 2:1 interlace. The system was demonstrated to a number of countries world-wide in an attempt get this as the defined standard. The equipment could display a composite signal, YUV components, and a digital recorder was included in the demonstration.

The Japanese system has not yet received world approval. A number of countries have held up approval waiting for results of studies. Questions about spectrum use and compatibility with current equipment and spectrum allocation continue to be debated. The FCC has established a program to define an advanced television system, much as they did for the approval of the NTSC standard in the 1950's. A set of subjective evaluations have now been scheduled for six candidate systems. These begin July 12, 1991, and conclude June 15, 1992.

The development of this standard is important to a wide segment of the industry. The system has impact far beyond interests of the entertainment industry. The system is expected to be a standard for medical displays, for the defense industry, and for the computer industry. Still-frame displays conforming to this standard could also be used in a large number of teleconference applications.

A.2.3 EDTV

EDTV (Extended Definition Television) has been widely discussed as an alternative to HDTV. In general, this is a television system with greater resolution that currently provided by the current NTSC and PAL standards, but requires less bandwidth than the Japanese HDTV candidate. Some of the changes involve only the receiver. Receivers today use a 30 Hz frame rate with 2:1 interlace. While interlace reduces the bandwidth required for a signal, it also reduces the vertical resolution, temporal resolution, and makes a artifact called "flicker" visible under some conditions.

Progressive scan is a system that eliminates the interlace (1:1), and displays all lines at a 60 Hz frame rate. This is already used in some computer displays. Some EDTV work also looked at the compatibility issue with existing equipment. In many cases, the system attempted to provide two signals: one that was compatible with existing equipment, and the other that could be used with an advanced receiver to increase the quality of the display.

A.2.4 FCC Advanced Television Standard Tests

The FCC's Advanced Television Test Center has announced schedules for the six advanced television systems under consideration for approval. These are shown in Table A-2.

Table A-2 ATTC Television System Tests

SYSTEM/PROPONENT	SCANNING	INTERLACE
Advanced Compatible TV — Sarnoff Res. Center/ATRC	525/59.94	1:1
Narrow MUSE — NHK, Japan Broadcasting Corp	1125/60	2:1
DigiCipher — ATVA (GI, MIT)	1050/59.94	2:1
DSC-HDTV: Digital Spectrum — Zenith, AT&T	787.5/59.94	1:1
ADTV: Advanced Digital TV — NA Phillips /ATRC	1050/59.95	2:1
ATVA Progressive System — MIT/ATVA	787.5/59.94	1:1

The equipment included in this test fall in both the HDTV and EDTV classes. Three use progressive scan (1:1 interlace)These tests must be completed before a U.S. standard for a more advanced [than NTSC] can be approved. Some of these are primarily analog signals; others will be transmitted only digitally.

A.2.5 Other (e.g. Computer Displays)

Computer displays may be used in several different teleconference applications. High resolution (e.g. 1100 line systems) with 8 bit gray scale or 24 bit color capability can be used for display of data and small moving images. Hardware is available for several systems that supports a window on the computer screen that can display a full motion image. For example, a 100 x 120 pixel image on a screen can provide a view of an individual equivalent to that of normal television programming. This work is being developed for multimedia sessions, but can be useful in a number of teleconference environments. An alliance between PictureTel and Intel promises to develop VLSI chips by 1992.

A number of new medical imaging systems are based on a television display. Ultrasound, magnetic resonance imaging, CAT scans, etc., all display the results of processing signals. Experts in many fields are concentrated in the largest cities, and near concentrations of research facilities. Teleconferences can provide quick access to this expertise.

A second explosive growth area is high resolution display of data. Conventional television sets are not capable of displaying large amounts of data, but a computer display can provide this in a teleconference. An existing workstation provides the basis for personal sessions. A large display can be added for groups.

A.3 Television Signal Generation

A summary of techniques, resulting bandwidths, and signal properties. The codec section will refer to these properties.

A.3.1 Television Raster

Scanning is the process for converting a two-dimensional optical image into a temporal waveform. Conventional analog systems define an area to be scanned. Each system defines the number of scan lines in a complete image, and the rate for transmission of a complete image. Figure A-2 shows the scan process. The image is scanned by a beam that starts in the upper left corner of the image, and continues across the image to the right side. The beam is then turned off and returns to the left side, and is slightly lower than the previous scan line. When the bottom of the image area is reached, the beam is turned off and returned to the upper left corner of the image. In image tubes and CRT displays time is required to return the beam from the right to the left sides, and from the bottom of the image to the top. These periods are called blanking periods are included in the signal. In general, about 16% of the time is reserved for horizontal retrace and 8% of the time is reserved for vertical retrace. The time spent scanning the image is the active picture scan time.

The analog television image is sampled in both the vertical and temporal dimensions. For the NTSC signal, there are 525 lines defining a frame (complete image). The number of active scan lines is 483. This sampling limits the resolution that can be displayed in the vertical direction. In analog systems, the resolution in the horizontal direction is limited by a low pass filter. Since the image is also sampled in the temporal dimension, this limits the rate of motion that can be displayed.

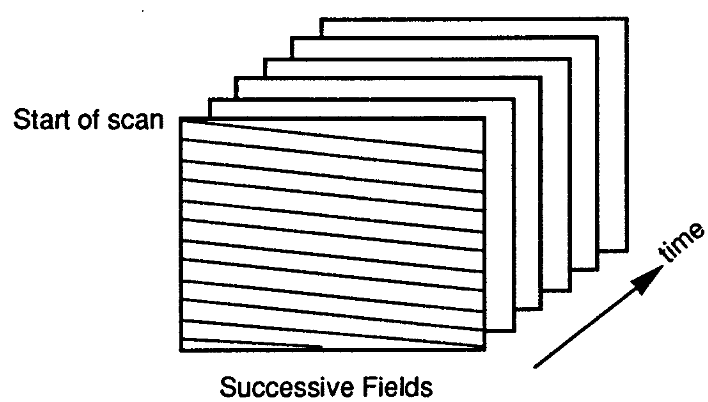


Figure A-2 Television Scanning

The horizontal scan frequency, f_h, is the product of the number of television lines and the frame rate: $f_h = 525 \times 29.97 = 15.734$ kHz. The desired horizontal resolution is the product of the aspect ratio and the vertical resolution. Dennis Kell reported results of subjective tests performed some years ago that measured the number of lines actually visible in vertical resolution. He found that the limit was approximately 77% due the the sampling. This factor is used to determine the bandwidth required for equal resolution in the vertical and horizontal directions. Table A-3 provides some comparisons of various systems described earlier.

Table A-3 Television Scanning Parameters

	NTSC	PAL	HDTV NHK	ACTV SARNOFF	ADTV PHILLIPS	H.261 CCITT	LOW - 1	LOW - 2
No of Scan Lines	525	625	1125	525	1050	288	262	262
Field Rate	59.94	50	59.94	59.94	59.94	29.97	29.97	29.97
Interlace	2	2	2	1	2	1	3	2
Aspect Ratio	1.33	1.33	1.67	1.78	1.78	1.33	1.33	1.33
Frame Rate	29.97	25	29.97	59.94	29.97	29.97	9.99	14.985
Kell Factor	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Hor Rate	15.73K	15.63K	33.72K	31.47K	31.47K	8.63K	2.62K	3.93K
Pixel / Line	700	833	1,875	933	1,867	383	349	349
Bandwidth	4.19M	4.95M	24.02M	11.16M	22.32M	1.26M	0.35M	0.52M
Pixels	287K	406K	1,646K	382K	1,529K	86K	71K	71K
Pixels/sec	8.59M	10.16M	49.32M	22.91M	45.83M	2.58M	0.71M	1.07M
Sampling Rate	11.01M	13.02M	63.22M	29.37M	58.74M	3.31M	0.91M	1.37M

A.3.2 Baseband Television signals

A.3.2.1 Analog Color Television Component Signals

A color television camera generates three color signals, red, blue, and green. Some cameras generate these signals by separating the optical image into three colors using dichroic mirrors. These three images are then imaged on separate camera tubes. The bandwidth of each of these signals is approximately 4.2 MHz or more for 525/60/2 systems. An RGB signal consists of three separate video signals for each of the colors. High quality monitors have an option for RGB inputs, and accept these three primary signals directly.

Most transmission systems transform the RGB signal into three other signals, and then combine these into a single signal for transmission. In the process of performing the transmission, the bandwidth of the signals is reduced so that the transmitted signal requires less bandwidth than needed for the RGB signal. The transformation is based on human vision which has reduced spatial response to both red and blue regions of the color spectrum. In effect, the eye does not perceive color in regions with high detail. The matrix produces a wideband luminance signal (Y), and two color difference signals as shown in Figure A-3. Two versions are called I, Q and U,V. These are similar, and differ by a simple 33° rotation of axes. For the following discussion, and for notational simplicity, the YUV designation will be used.

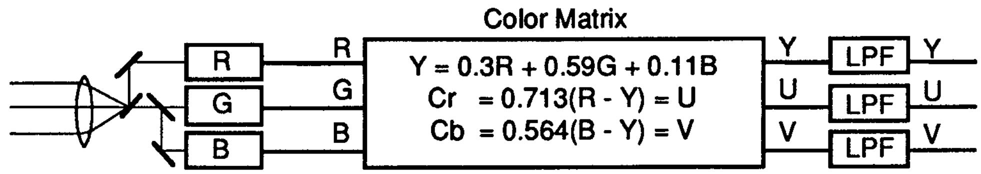


Figure A-3 Color Television Signal Components.

Two different techniques are used for combination of the YUV signals. The one used since the mid 1950s uses a frequency multiplex of the color difference signals and the luminance signal using a subcarrier. A more recent technique uses a time-multiplexed technique to combine the three signals.

A.3.2.2 Composite Color Television Signal Generation

The frequency spectrum of a television signal is not continuous, but is concentrated at harmonics of the horizontal scan frequency, and the vertical frame frequency. This is caused by sampling in the vertical direction, sampling in the temporal direction, and the inherent redundancy of the television image.

The design of the composite color signals used in broadcast today had two objectives: one was to form a signal that was compatible with monochrome receivers at the time the standard was created, and the other was to transmit a color signal in the same bandwidth channels that had been approved for monochrome transmission (6 MHz in the United States). Tests showed that frequencies that were harmonics of the horizontal line rate were of high visibility, and frequencies that were in between these harmonics were of low visibility. A color subcarrier is used that is an odd multiple of half the line rate. Since the color difference signals have a frequency content similar to the luminance signal, the energy peaks in the modulated subcarrier were of low visibility.

Figure A-4 shows a simplified block diagram illustrating the techniques used to form a composite color signal. The NTSC specification uses the YIQ components, with a 4.2 MHz Y bandwidth, a 1.2 MHz I bandwidth, and a 0.6 MHz Q bandwidth, and a 33° rotation of the modulating subcarrier. The low-pass filtering of the composite signal causes the I signal to be asymmetric. In practice, most receivers use YUV decoding, and use a 4.2 MHz Y channel filter and 0.6 MHz U and V channel filters.

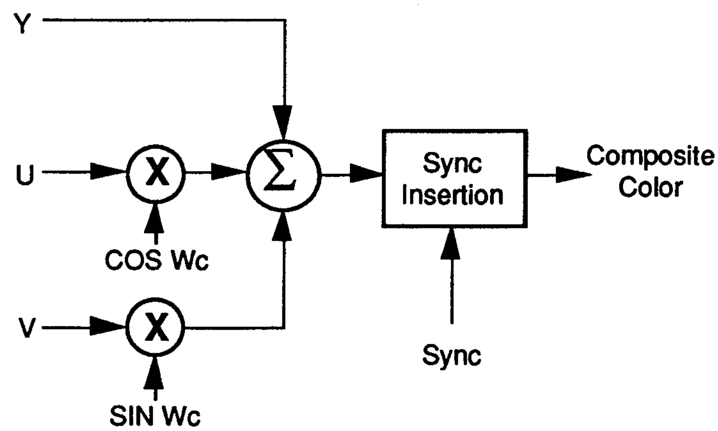


Figure A-4 Composite Color Television Signal Formation

The European PAL signal is similar to NTSC. The Y channel bandwidth is 5 MHz, and the U and V bandwidths are approximately 1 MHz. The color subcarrier is slightly more complex, and has a 90° phase shift on alternate lines to further reduce the subcarrier visibility, but other properties are similar.

A.3.2.3 MAC - Multiplexed Analog Components Signal Generation

The MAC signal format was devised to help solve a number of problems with the composite signal, especially in the studio. One of these is the difficulty in separating the three color components from the composite signal, and the restriction in color difference signal bandwidth. One of the key techniques used in broadcast preparation is color keying. This allows two different signals to be combined, and forms the basis for most of the news programs, and for many special effects in entertainment programs. In this technique, the foreground image is taken against a blue background. The color key processor detects this background, and inserts the background picture any time that the blue background is found in the foreground signal. Chroma-key works much better with high bandwidth color signals that are free from luminance crosstalk.

A second reason for the new format is the use of FM transmission for studio to studio links, and for digital processing equipment used in the studios. Equipment for processing time-multiplexed components is simpler, and produces fewer artifacts than equipment that must decode the composite signal for processing, and then reform the composite signal. The processing blocks for MAC signal formation are shown in Figure A-5. Each of the three signals is first stored in a buffer, then is read out from the buffer at a faster rate. The resulting signals are then combined in a time-multiplexed stream.

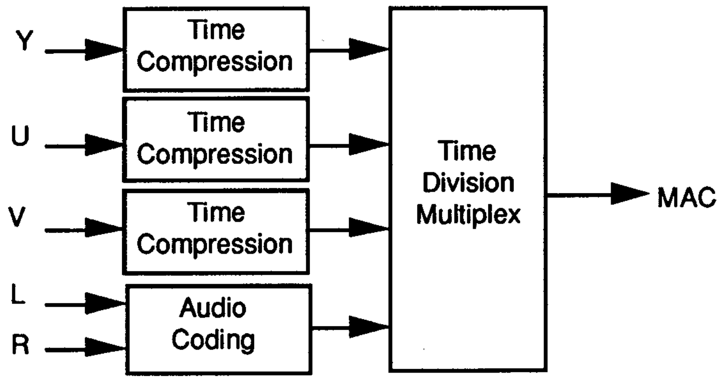


Figure A-5 MAC Encoder Diagram

Assume that the Y bandwidth is 4 MHz, and the U and V channel bandwidths are each 2 MHz. If a 3:2 time compression factor is used for the Y channel, and a 3:1 time compression is used for the U and V channels, then then the bandwidth of all three time-compressed signals will be approximately 6 MHz. This is illustrated in Figure A-6. Two lines of YUV signals are shown on the left. After passing through the time compression buffers, these signals now have period of no signal as shown on the right. These three channels can now be combined using a YUYV sequence on two lines. Synchronization signals are then added, and some systems use this region to include the audio information.

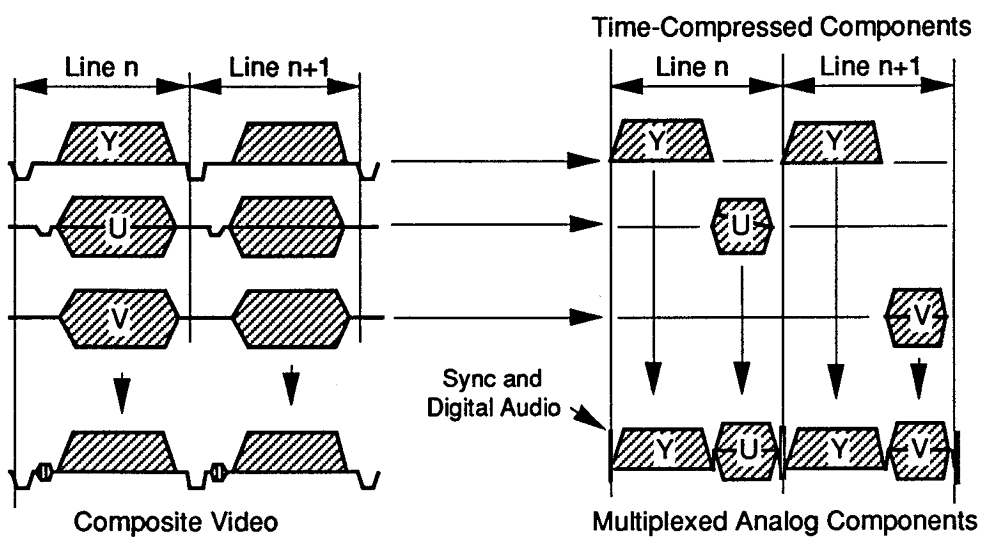


Figure A-6 MAC Signal Formation

An illustration of the what is happening in the frequency domain during these operations is shown in Figure A-7. The video components are shown at the left. The reduced bandwidth of the U and V signals is caused by filtering. The spectrum of the composite signal is shown in the center, and shows the overlap of luminance and color difference signals. The time-compressed frequencies are shown on the right, and show an expansion factor equal to the time compression factor. The spectrum of the MAC signal will alternately be that of the time compressed Y, U, Y, and V signals as each is connected to the channel.

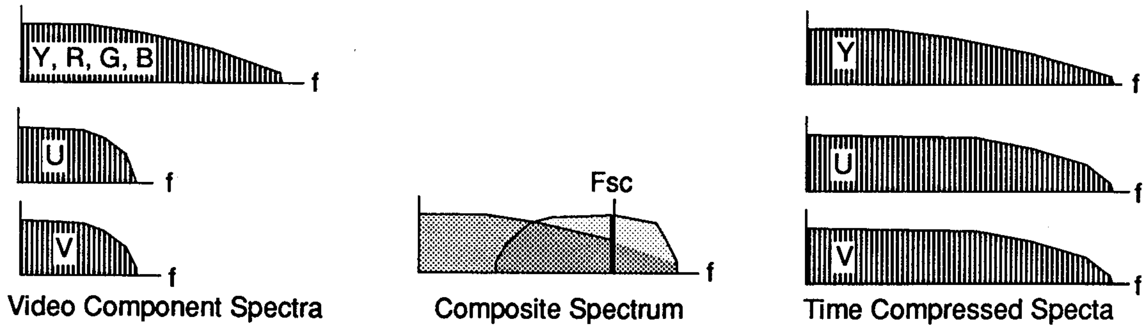


Figure A-7 Analog Video Signal Frequencies

A.3.3 Audio

There are four evolving categories for program-associated audio. Broadcast television has been a 5 MHz channel that is transmitted using an FM carrier that is above the highest video signal frequency — 4.5 MHz in the United States. Stereo program audio is now becoming a second standard with 15 kHz bandwidth.

Conference audio has no established standard, but two ranges seem to be evolving. One of these is approximately 3.5 kHz wide, and is similar to telephone quality. This is frequently used in very low bandwidth applications, e.g. 64K and 128 kb/s channels. In these sessions, the rate for audio transmission is usually 8 to 16 kb/s. Audio from these codecs is intelligible, but is obviously of lower quality.

In higher bandwidth sessions of 384 kb/s and higher can provide a 64 kb/s channel for audio. Audio codecs can provide a 7 kHz bandwidth for the audio signal. This wider bandwidth provides a much higher quality signal that comes much closer to stereo channel performance, and delivers a "sound" that is close to that found in a face to face meeting.

<<<Echo control>>>

A.4 Digital Coding

Digital coding has several applications. First, it provides a means for sending images or speech at lower required bandwidths than attainable with analog transmission techniques. Second, it is employed in networks employing digital transmission media. Third, digital communications can be used in noisy environments without introducing noise into the transmitted signal. Digital coding is of interest in television program production since no noise is added during the many generations of production.

The first step is the initial quantization of an image. The sampling rate for a typical NTSC signal approximately 11 MHz, and an eight bit quantizer is needed for highest quality. The results in a digital signal of approximately 90 Mb/s. Simple PSK modulation requires a bandwidth in excess of 45 MHz. The video signal is highly redundant, and digital processing can reduce the number of bits for transmission while retaining the actual information in the image. These coders can also be used at higher rates to further reduce the bit rates, with modest change to the image. At some point, any compression technique will begin to introduce artifacts — visible changes to the reproduced image. In the discussion that follows, some of the major coding techniques will be discussed, and the level where artifacts begin to appear will be described.

A.4.1 DPCM

A simplified block diagram of a digital DPCM (Differential Pulse Coded Modulation) coder is shown in Figure A-8. Instead of directly sending the PCM samples, the quantized difference between the actual signal and a predicted signal is sent. Two elements that control the amount of coding gain and quality of the image are the predictor and the quantizer.

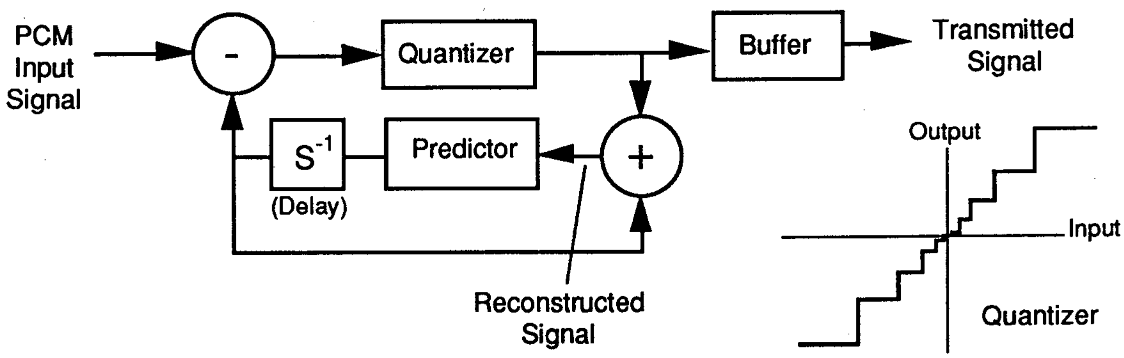
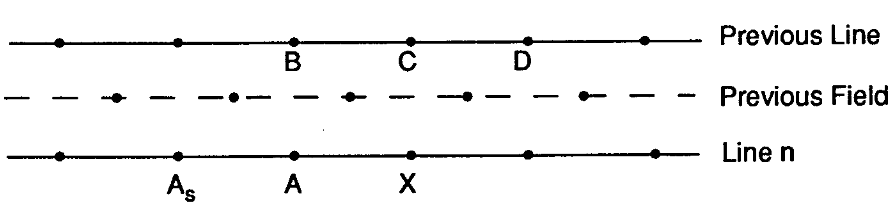


Figure A-8 Digital DPCM Coder

The predictor can take a large number of forms that depend on the signal format. Figure A-9 shows the geometrical relations between samples in a typical television image. The simplest predictor is derived from the previous horizontal element. In the figure below, X = A. Intra-field predictors use samples in the same field. When samples from the current line and a previous line are used in the predictor, then large steps in both the horizontal and vertical directions can be included in the prediction. Figure A-9 shows a two dimensional predictor used in some component coders. If the signal is a composite signal, then a more complex predictor is needed because of the presence of the color subcarrier. The predictor is optimized to minimize the entropy in the difference signal. The peak to peak amplitude of the difference signal is smaller than that of the input signal, and many samples are small.



$X = \frac{A + D}{2}$, where X is the sample being predicted

Figure A-9 Example of Two Dimensional Predictor

The visibility properties of the difference signal are different than those of the input signal. Large differences occur near edges. The visibility of coarse quantization near an edge is lower than in low detail areas. This property is used in the design of the quantizer. Small differences have small quantizing steps, and becomes increasingly coarser for large difference signals. This further reduces the number of bits that need to be transmitted for a sample.

If the quantized code words are of equal length, then the output from a DPCM coder is a constant rate. The distribution of difference signals is non-uniform — small differences are much more probable than large edges. An entropy coder can be used in quantization to either further reduce the bit rate, or to provide more quantization steps for a given bit rate. If an entropy coder is used, than a buffer may be required for interface to a constant rate channel.

The coder can also be adaptive. This allows values in the quantizer to adapt to the current image, or to a portion of the image. The size of the quantization steps would be small in regions of small peak to peak differences, and becomes coarser in regions of high detail producing larger peak to peak difference.

Another option is the use of multiple predictors and quantizers. Several codecs have been designed that code a portion of the image with several variations. The one providing the smallest number of bits, or the highest quality is then the one that is transmitted.

When the predictor uses samples from previous frames, the the codec becomes an interframe codec. The visual properties in the vertical direction are different than those from intraframe predictors. A television image of a still object has very small entropy in the frame difference signal. The entropy increases in the presence of motion. The human visual system is acute for still images, but this acuity is reduced in the presence of moderate motion. Therefore, large frame to frame differences will exist in the presence of motion, and can be quantized using fewer bits. The price required for this technique is one or more fields of memory for the predictor. This was prohibitive a decade ago, but is now practical.

DPCM video codecs generally operate at bit rates of 3 to 5 bits per sample. Artifacts observed with these codecs is reduced edge sharpness, and may introduce increased noise near the edges.

A.4.2 Conditional Replenishment and Motion Compensation

A variation of a DPCM coder is used in coders that exploit the temporal resolution properties. This has produced some large compression ratios. The conditional replenishment codec examines regions of an image with small frame differences between a stored image and the input signal. The coder determines whether any update is needed, and updates only those that exceed a threshold.

Motion compensation determines the areas of an image that are moving. The codec estimates the bounds of a moving area, the direction, and the velocity. This is then used as part of the prediction. As an example, consider an image from a camera that is slowly panning in the horizontal direction. If the direction and velocity are accurately determined, and if no relative motion is present, then the only change that needs to be transmitted is a narrow strip along one edge that has been uncovered. Another example is a car moving horizontally across the screen. The only portion of an image that must be sent is the area behind the car that was behind the car in the previous frame.

These coders are used a rates from less than one bit per pixel to 4 bits per pixel. They provide very high quality during periods with little or no motion in the image. Artifacts become visible, and can be pronounced with larger amounts of image motion and at lower bit rates.

A.4.3 Transform

A number of transforms have been used for images. A suitable transform decorrelates the image, and has a fast transform. One that is frequently used is the discrete cosine transform (DCT). These codecs are frequently employed at lower rates. A DCT takes a block of input samples and produces a set of output samples with increasing frequency coefficients. The DCT decorrelates the image, i.e., the entropy of the coefficients is much smaller than in the input samples. A block diagram for a DCT is shown in Figure A-10. A set of input samples is formed to a block. These samples are weighted and summed in the computation matrix producing a new set of samples representing frequency terms. These coefficients are then ordered and sequentially transmitted.

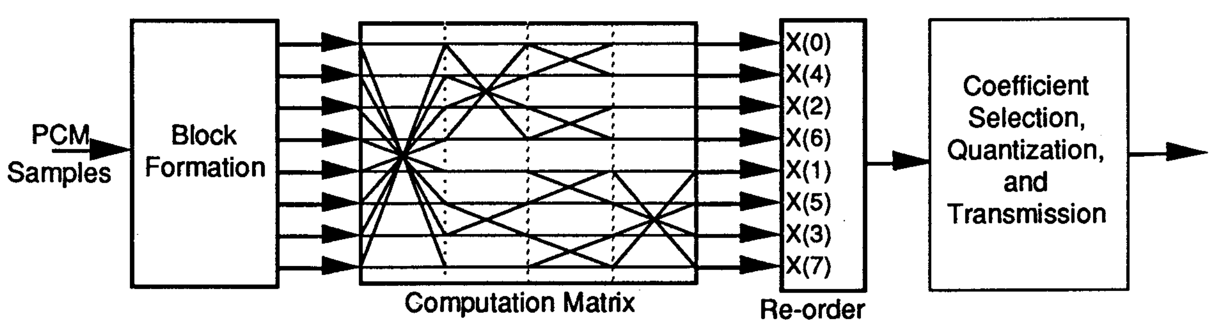


Figure A-10 DCT Coder, N=8

The properties of the transform coefficients provide a number of advantages for coding. First, the value of many of the coefficients is near zero, and need not be transmitted or require a smaller number of bits. Second, the visibility of some of the coefficients is low. Some codecs use this property and ignore some of the higher frequency coefficients. This can be viewed as a two dimensional filter. Third, the visibility of quantization of higher frequency coefficients is smaller than those at low frequency, so these can be sent with fewer bits.

Images can be coded with one, two, or three dimensional transforms. For the DCT, a two dimensional transform can be produced by first applying a one dimensional transform to the horizontal line. These coefficients are then placed in a buffer containing a number of lines equal to the number of coefficients. These stored coefficients are then applied to a second one-dimensional coder. The resulting output is a two dimensional transform. This can also be repeated in the temporal dimension, but the amount of memory becomes large.

Transform coders require many computations. The fast algorithm requires

$$\frac{3}{2}N\left(\log_2 \frac{N}{2}\right) + 2 \text{ additions, and } N(\log_2 N) - \frac{3}{2}N + 4 \text{ multiplications.} \qquad (1)$$

Bit-rate reductions with transform systems are possible because of two factors: the resulting energy in the transform coefficients, and the visibility of the coefficients. Figure A-11 shows the energy found in transform coefficients in typical images. The strategy is to transmit coefficients with the highest energy. Some codecs select a set of coefficients to transmit based on analyzing averages from a training set of images. Each coefficient is assigned a specific number of bits, and a quantization table. Other systems analyze the results from each block, and send those with the largest energy. This can produce a better image, but the coefficient address must be sent with the coefficient value. An entropy coder can also be used, that uses variable length codes for coefficient values. In most cases a buffer is then needed to smooth the flow, and buffer overflow prevention modes are required.

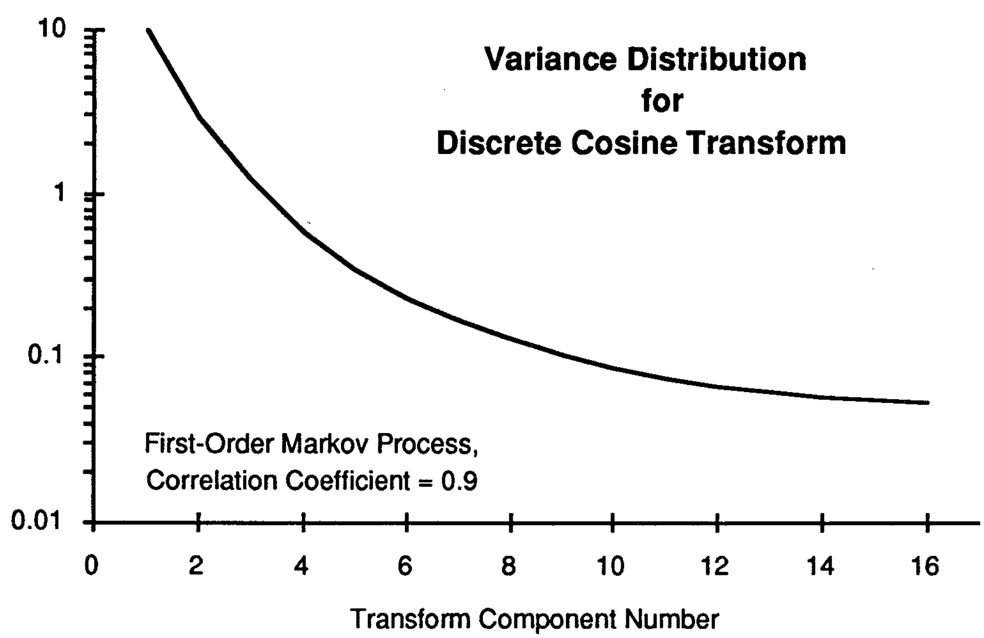


Figure A-11 Transform Coefficient Variance

Two dimensional transforms have been used with systems with 1 to 4 bits per pixel rate, and provide higher image quality for a given bit rate than that of an intraframe predictive coder. Due to the need for many fast multipliers and adders, these have been used primarily at lower rates or for still images. This situation is changing with the development of faster DSP chips.

Transforms provide a wider operating range that can be defined as the range from the point where artifacts first appear to the point where these artifacts become very objectionable. This is a gradual loss of resolution (a "softening" of the image) at first. As the rate is further reduced, more coefficients in the block are dropped. This eventually produces a visible block structure in the image.

A.4.4 Hybrid

Hybrid coders combine transforms and differential coders. In general, the DPCM coder requires two additions for computation of the difference signal, and several adders and multipliers used in the predictor. Equipment complexity is reduced in hybrid coders. Four hybrid coders are of interest:

- One dimensional DCT and DPCM of coefficients. One dimensional DCT and DPCM of coefficients performs nearly as well as a two dimensional DCT.
- Two dimensional DCT and DPCM of coefficients. Two dimensional DCT and DCPM of interframe coefficients performs nearly as well as a three dimensional DCT.
- Interframe DPCM and two dimensional DCT.
- Conditional replenishment and two dimensional DCT.

A.4.5 Vector Quantization

Vector quantization takes a block of samples, and uses an adaptive "code book" to look up the a code to represent the block.

Appendix B

Link Budgets

This appendix gives the link budgets used for the satellite design in Chapter 5. The Integrated Video satellite uses on-board processing and switching. Link budgets are given for uplinks and downlinks, for the three different types of user terminals:

- Small user with 1.2 m terminal and 2 Mb/s transmission rate,
- Medium user with 1.8 m terminal and 6 Mb/s transmission rate,
- Large user with 3 m terminal and 6 Mb/s transmission rate.

There are six link budget calculation tables:

Fig. B-1: Small User Uplink Budget: 1.2 m diameter, 2 Mb/s, 98% Availability in Region E
Fig. B-2: Medium User Uplink Budget: 1.8 m diameter, 6 Mb/s, 99% Availability in Region E
Fig. B-3: Large User Uplink Budget: 3 m diameter, 6 Mb/s, 99.5% Availability in Region E
Fig. B-4: Small User Downlink Budget: 1.2 m diameter, 98% Availability in Region E
Fig. B-5: Medium User Downlink Budget: 1.8 m diameter, 99%+ Availability in Region E
Fig. B-6: Large User Downlink Budget: 3 m diameter, 99.5%+ Availability in Region E

Parameter	Link Analysis Value Units	Link Data Value Units	Remarks
Carrier Frequency		29.75 GHz	**Uplink, VSAT to S/C**
VSAT Transmit Power	5.44 dBW	**3.5 W**	
Line Loss	1.00 dB		
VSAT Antenna Gain	49.24 dBi		
VSAT Antenna Diameter		**1.20 m**	47.2 in
Antenna Efficiency		60 %	
EIRP	53.69 dBW		
Free Space Loss	213.52 dB		
Range		38,000 km	
VSAT Pointing Loss	1.00 dB		
Atmosphere Loss	0.60 dB		
Rain Margin	**3.10 dB**	**98.00 %**	**Annual Avail. in Reg. E,**
Net Path Loss	218.22 dB	**175 hr/yr outage**	
S/C Antenna Gain	45.83 dBi		**28 beams, 0.87° beams**
S/C Antenna Diameter		0.81 m	31.9 in
Antenna Efficiency		60 %	
Edge of Coverage Gain Loss	4.30 dB		
Line Loss	1.00 dB		
System Temp. @ Rcvr. Input	26.80 dB-K	479 K	
S/C Antenna Temp.		280 K	
Receive Line Temp.		130 K	
S/C Receiver Temp.		230 K	Noise Figure = 2.5 dB
Effective G/T	13.73 dB/K		
Received Carrier Level		-124.00 dBW	Flux = -113.6 dBW/m^2
Boltzmann's Constant	-228.60 dBW/Hz-K		
Received C/No	77.80 dB-Hz		
Data Rate	63.01 dB-Hz	**2.00 Mb/s**	TDM, 64 kb/s to 512 kb/s
Interference Degradation	1.80 dB		C/I = 16.0 dB
Modem Implementation Loss	2.00 dB		
Coding Gain	5.30 dB		**Viterbi coding, R=1/2 soft decision**
Available Eb/No	16.29 dB		
Required Eb/No	13.20 dB	**1E-06 BER**	**D-QPSK**
Margin	3.09 dB		

UPLINK	**98.0 %**	**Annual Avail. in Reg. E,**	**175 hr/yr outage**
	2.00 Mb/s	**Data rate**	
	28 beams	**0.87° beams**	
VSAT parameters:	**1.20 m**	**VSAT diameter**	
	3.5 W	**VSAT transmit power**	

Figure B–1: Small User Uplink Budget: 1.2 m diameter, 2 Mb/s, 98% Availability in Region E

C2

Parameter	Link Analysis Value Units	Link Data Value Units	Remarks
Carrier Frequency		29.75 GHz	**Uplink, VSAT to S/C**
VSAT Transmit Power	10.00 dBW	**10.0 W**	
Line Loss	1.00 dB		
VSAT Antenna Gain	52.77 dBi		
VSAT Antenna Diameter		**1.80 m**	70.9 in
Antenna Efficiency		60 %	
EIRP	61.77 dBW		
Free Space Loss	213.52 dB		
Range		38,000 km	
VSAT Pointing Loss	1.00 dB		
Atmosphere Loss	0.60 dB		
Rain Margin	**6.50 dB**	**99.00 %**	**Annual Avail. in Reg. E,**
Net Path Loss	221.62 dB	**88 hr/yr outage**	
S/C Antenna Gain	45.83 dBi	**28 beams,**	**0.87° beams**
S/C Antenna Diameter		0.81 m	31.9 in
Antenna Efficiency		60 %	
Edge of Coverage Gain Loss	4.30 dB		
Line Loss	1.00 dB		
System Temp. @ Rcvr. Input	26.80 dB-K	479 K	
S/C Antenna Temp.		280 K	
Receive Line Temp.		130 K	
S/C Receiver Temp.		230 K	Noise Figure = 2.5 dB
Effective G/T	13.73 dB/K		
Received Carrier Level		-119.32 dBW	Flux = -108.9 dBW/m^2
Boltzmann's Constant	-228.60 dBW/Hz-K		
Received C/No	82.48 dB-Hz		
Data Rate	67.78 dB-Hz	**6.00 Mb/s**	
Interference Degradation	1.80 dB		C/I = 16.0 dB
Modem Implementation Loss	2.00 dB		
Coding Gain	5.30 dB		**Viterbi coding, R=1/2 soft decision**
Available Eb/No	16.20 dB		
Required Eb/No	13.20 dB	**1E-06 BER**	**D-QPSK**
Margin	3.00 dB		

UPLINK	**99.0 %**	**Annual Avail. in Reg. E,**	**88 hr/yr outage**
	6.00 Mb/s	**Data rate**	
	28 beams	**0.87° beams**	
VSAT parameters:	**1.80 m**	**VSAT diameter**	
	10.0 W	**VSAT transmit power**	

Figure B–2: Medium User Uplink Budget: 1.8 m diameter, 6 Mb/s, 99% Availability in Region E

Parameter	Link Analysis Value Units	Link Data Value Units	Remarks	
Carrier Frequency		29.75 GHz	**Uplink, VSAT to S/C**	
VSAT Transmit Power	10.68 dBW	**11.7 W**		
Line Loss	1.00 dB			
VSAT Antenna Gain	57.20 dBi			
VSAT Antenna Diameter		**3.00 m**		118.1 in
Antenna Efficiency		60 %		
EIRP	66.89 dBW			
Free Space Loss	213.52 dB			
Range		38,000 km		
VSAT Pointing Loss	1.00 dB			
Atmosphere Loss	0.60 dB			
Rain Margin	**11.60 dB**	**99.5 %**	**Annual Avail. in Reg. E,**	
Net Path Loss	226.72 dB	**44 hr/yr outage**		
S/C Antenna Gain	45.83 dBi		**28 beams,**	**0.87° beams**
S/C Antenna Diameter		0.81 m		31.9 in
Antenna Efficiency		60 %		
Edge of Coverage Gain Loss	4.30 dB			
Line Loss	1.00 dB			
System Temp. @ Rcvr. Input	26.80 dB-K	479 K		
S/C Antenna Temp.		280 K		
Receive Line Temp.		130 K		
S/C Receiver Temp.		230 K	Noise Figure =	2.5 dB
Effective G/T	13.73 dB/K			
Received Carrier Level		-119.30 dBW	Flux =	-108.9 dBW/m^2
Boltzmann's Constant	-228.60 dBW/Hz-K			
Received C/No	82.50 dB-Hz			
Data Rate	67.78 dB-Hz	**6.000 Mb/s**		
Interference Degradation	1.80 dB		C/I =	16.0 dB
Modem Implementation Loss	2.00 dB			
Coding Gain	5.30 dB		**Viterbi coding,**	**R=1/2 soft decision**
Available Eb/No	16.21 dB			
Required Eb/No	13.20 dB	**1E-06 BER**	**D-QPSK**	
Margin	3.01 dB			

UPLINK	**99.5 %**	**Annual Avail. in Reg. E,**	**44 hr/yr outage**
	6.00 Mb/s	**Data rate**	
	28 beams	**0.87° beams**	
VSAT parameters:	**3.00 m**	**VSAT diameter**	
	11.7 W	**VSAT transmit power**	

Figure B–3: Large User Uplink Budget: 3 m diameter, 6 Mb/s, 99.5% Availability in Region E

Parameter	Link Analysis Value Units	Link Data Value Units	Remarks	
Carrier Frequency		19.95 GHz	**Downlink, S/C to VSAT**	
S/C Transmit Power	11.17 dBW	**13.1 W**	Power per channel	
Line Loss	1.00 dB			
S/C Antenna Gain	45.77 dBi			**28 beams over CONUS**
Edge of Coverage Gain Loss	4.30 dB			
S/C Antenna Diameter		1.20 m	0.87° beams	47.2 in
Antenna Efficiency		60 %		
EIRP	51.65 dBW			
Free Space Loss	210.04 dB			
Range		38,000 km		
VSAT Pointing Loss	0.50 dB			
Atmosphere Loss	0.40 dB			
Rain Margin	**1.40 dB**	**98.00 %**	**Annual Availability in Region E,**	
Net Path Loss	212.34 dB	**175 hr/yr outage**		
VSAT Antenna Gain	45.77 dBi			
VSAT Diameter		**1.20 m**		47.2 in
Antenna Efficiency		60 %		
Line Loss	1.00 dB			
System Temp. @ Rcvr. Input	25.04 dB-K	319 K		
VSAT Antenna Temp.		100 K		
Receive Line Temp.		290 K		
VSAT Receiver Temp.		180 K	Noise Figure =	2.1 dB
Effective G/T	19.74 dB/K			
Received Carrier Level		-115.92 dBW	Flux =	-113.2 dBW/m^2
Boltzmann's Constant	-228.60 dBW/Hz-K			
Received C/No	87.64 dB-Hz			
Data Rate	77.32 dB-Hz	54.00 Mb/s		
Interference Degradation	1.10 dB		C/I =	16.0 dB
Modem Implementation Loss	1.00 dB			
Coding Gain	5.30 dB		**Viterbi, R=1/2**	
Available Eb/No	13.51 dB			
Required Eb/No	10.50 dB	**1E-06 BER**	**BPSK**	
Margin	3.01 dB			

DOWNLINK	**98.0 %**	**Annual Availability in Region**	**175 hr/yr outage**
	54 Mb/s	**Data rate**	
	28 beams	**0.87° beams**	
	13.1 W	**S/C power per channel**	
	734 W	**Total S/C RF power (2 channels per beam)**	
VSAT parameters:	**1.2 m**	**VSAT diameter**	

Figure B–4: Small User Downlink Budget: 1.2 m diameter, 98% Availability in Region E

Parameter	Link Analysis Value Units	Link Data Value Units	Remarks	
Carrier Frequency		19.95 GHz	**Downlink, S/C to VSAT**	
S/C Transmit Power	11.14 dBW	**13.0 W**	Power per channel	
Line Loss	1.00 dB			
S/C Antenna Gain	45.77 dBi			**28 beams over CONUS**
Edge of Coverage Gain Loss	4.30 dB			
S/C Antenna Diameter		1.20 m	0.87° beams	47.2 in
Antenna Efficiency		60 %		
EIRP	51.61 dBW			
Free Space Loss	210.04 dB			
Range		38,000 km		
VSAT Pointing Loss	0.50 dB			
Atmosphere Loss	0.40 dB			
Rain Margin	**3.10 dB**	**99.00 %**	**Annual Availability in Region E,**	
Net Path Loss	214.04 dB	**88 hr/yr outage**		
VSAT Antenna Gain	49.30 dBi			
VSAT Diameter		**1.80 m**		70.9 in
Antenna Efficiency		60 %		
Line Loss	1.00 dB			
System Temp. @ Rcvr. Input	25.04 dB-K	319 K		
VSAT Antenna Temp.		100 K		
Receive Line Temp.		290 K		
VSAT Receiver Temp.		180 K	Noise Figure =	2.1 dB
Effective G/T	23.26 dB/K			
Received Carrier Level		-114.14 dBW	Flux =	-115.0 dBW/m^2
Boltzmann's Constant	-228.60 dBW/Hz-K			
Received C/No	89.43 dB-Hz			
Data Rate	77.32 dB-Hz	54.00 Mb/s		
Interference Degradation	1.10 dB		C/I =	16.0 dB
Modem Implementation Loss	1.00 dB			
Coding Gain	5.30 dB		**Viterbi, R=1/2**	
Available Eb/No	15.30 dB			
Required Eb/No	10.50 dB	**1E-06 BER**	**BPSK**	
Margin	4.80 dB			

DOWNLINK	**99.0 %**	**Annual Availability in Region**	**88 hr/yr outage**
	54 Mb/s	**Data rate**	
	28 beams	**0.87° beams**	
	13.0 W	**S/C power per channel**	
	728 W	**Total S/C RF power (2 channels per beam)**	
VSAT parameters:	**1.8 m**	**VSAT diameter**	

Figure B–5: Medium User Downlink Budget: 1.8 m diameter, 99%+ Availability in Region E

Parameter	Link Analysis Value Units	Link Data Value Units	Remarks	
Carrier Frequency		19.95 GHz	**Downlink, S/C to VSAT**	
S/C Transmit Power	11.14 dBW	**13.0 W**	Power per channel	
Line Loss	1.00 dB			
S/C Antenna Gain	45.77 dBi			**28 beams over CONUS**
Edge of Coverage Gain Loss	4.30 dB			
S/C Antenna Diameter		1.20 m	0.87° beams	47.2 in
Antenna Efficiency		60 %		
EIRP	51.61 dBW			
Free Space Loss	210.04 dB			
Range		38,000 km		
VSAT Pointing Loss	0.50 dB			
Atmosphere Loss	0.40 dB			
Rain Margin	**5.70 dB**	**99.50 %**	**Annual Availability in Region E,**	
Net Path Loss	216.64 dB	**44 hr/yr outage**		
VSAT Antenna Gain	53.73 dBi			
VSAT Diameter		**3.00 m**		118.1 in
Antenna Efficiency		60 %		
Line Loss	1.00 dB			
System Temp. @ Rcvr. Input	25.04 dB-K	319 K		
VSAT Antenna Temp.		100 K		
Receive Line Temp.		290 K		
VSAT Receiver Temp.		180 K	Noise Figure =	2.1 dB
Effective G/T	27.69 dB/K			
Received Carrier Level		-112.30 dBW	Flux =	-117.6 dBW/m^2
Boltzmann's Constant	-228.60 dBW/Hz-K			
Received C/No	91.26 dB-Hz			
Data Rate	77.32 dB-Hz	54.00 Mb/s		
Interference Degradation	1.10 dB		C/I =	16.0 dB
Modem Implementation Loss	1.00 dB			
Coding Gain	5.30 dB		**Viterbi, R=1/2**	
Available Eb/No	17.14 dB			
Required Eb/No	10.50 dB	**1E-06 BER**	**BPSK**	
Margin	6.64 dB			

DOWNLINK	**99.5 %**	**Annual Availability in Region**	**44 hr/yr outage**
	54 Mb/s	**Data rate**	
	28 beams	**0.87° beams**	
	13.0 W	**S/C power per channel**	
	728 W	**Total S/C RF power (2 channels per beam)**	
VSAT parameters:	**3.0 m**	**VSAT diameter**	

Figure B–6: Large User Downlink Budget: 3 m diameter, 99.5%+ Availability in Region E

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Appendix C

Cost Comparison

This appendix presents a cost comparison of three satellite system concepts developed under NASA Contract No. NAS3-25092.

Task 4: Mesh VSAT satellite system

Task 5: Integrated Video satellite system

Task 6: B-ISDN satellite system (2 concepts)

Cost assumptions, comparison tables, and cost conclusions are given. The comparison shows that the B-ISDN system has lower user costs, primarily due to its higher capacity.

C.1 Cost Assumptions and Methodology

Costing assumptions were reasonably constant over the three studies with satellite wet mass being very similar, but there being differences in end-of-life power. The following is a list of these assumptions and differences for the three concepts.

All Concepts:

- Commercial system costing (versus NASA or DoD program).
- Launch on Atlas IIAS; launch insurance at 16%.
- User costs in $/min, 1992 $; 18% return on investment.
- Develop and manufacture two satellites with contract award in 2002 and launch in 2006.
- 15-yr on-orbit life.
- Satellite design uses year 2000 technology: ion thrusters for on-orbit station keeping; advanced NiH batteries; and thin silicon solar cells.
- Satellite wet mass 1,770 kg to 1,890 kg; power 3.5 kW to 5.6 kW.
- Payloads use baseband processing and switching except B-ISDN Architecture 1.
- Ground terminal use ranges from 1 to 8 hr/day; 250 days per year.
- System utilization is assumed to be 15% for all systems except the B-ISDN Architecture 2 which has 20% utilization.

Mesh VSAT Satellite:

- Uses multi-carrier demodulators and baseband switching.

B-ISDN Satellite:

- IF Switching and no on-board processing for Architecture 1.
- Demodulation and baseband switching for Architecture 2.
- Smaller (0 .4 °), scanning spot beams used for Architecture 2.
- System utilization is assumed higher (20% versus 15%) for Architecture 2.

Integrated Video Satellite:

- Uses multi-carrier demodulators and baseband switching.

User costs per minute are derived from the annualized costs for the ground terminal and the space segment (satellite plus network control) costs. The user cost per minute is based on (1) the number of minutes per year utilization of the ground terminal, and (2) the proportional use of the space segment capacity by the single user. This is expressed by the formula on the "Cost Formulas" table (Table C-7).

C.2 Comparison Tables

There are eight tables which present a side-by-side comparison of the mesh VSAT, B-ISDN (2 concepts), and integrated video satellite system design concepts.

Table C-1: "Comparison of System Designs" summarizes the satellite, ground terminal, and system parameters. Note that the satellite mass is approximately the same (same launch vehicle, Atlas 2AS), but there is a 4 times difference in circuit capacity among the different concepts. The B-ISDN Architecture 2 has 0 .4 ° spot beams versus 0 .9 ° or larger spot beams for the other concepts.

Table C-2: "Downlink Performance Comparison" gives parameters from the downlink link budget calculations. Note the higher EIRP for the B-ISDN Architecture 2, and the use of concatenated codes with 11 dB coding gain for the two B-ISDN concepts.

Table C-3: "Uplink Performance Comparison" gives parameters from the uplink link budget calculations. Large VSATs are required for the higher data rates of the B-ISDN systems.

Table C-4: "Space plus Network Control Costs" summarize space segment costs and network control center costs, and adds them together. For comparison purposes, the bottom of the table gives the estimated total ground terminal cost based on number of ground terminals (see Table C-1) and cost of a single ground terminal (see Table C-6). The B-ISDN systems have lower total ground terminal costs

Table C-5: "Space plus Network Control Costs per Minute" is based on the data in the previous table, the total satellite capacity, and the assumed overall satellite utilization.

For example, consider the Mesh VSAT system with \$216 M annual space plus NCC cost. The number of equivalent "full capacity" minutes use per year is the number of minutes in a year (525,960) times the satellite utilization (15%) or 78,894 min/yr. Dividing \$216 M by this number gives \$2,738/min for use of the full capacity (5.4 Gb/s). The cost per Gb/s is \$507/min (\$2,738/5.4), and the cost per Gb transmitted is \$8.45 (\$507/60, since there are 60 seconds per minute).

Table C-6: "Ground Terminal Cost Comparison" is given for the different size terminals used in the different systems. The B-ISDN terminals are more expensive due to higher data rates.

Capital costs are amortized over 15 years at 18% interest and added to O&M costs in order to obtain the annual ground terminal cost. The cost per minute operation of the ground terminal is the annual cost divided by the number of minutes used per year.

For example, the 1.8 m Mesh VSAT terminal has an annual cost of $13,500. Operation for 1 hr/day, 250 working days per year, is 15,000 minutes per year. Thus the effective ground terminal cost per minute is $0.90/min ($13,500/15,000).

Table C-7: "Cost Formulas and Values for 4 Satellite System Concepts" are given. The formula at the bottom is used to determine user cost per minute. The user $/min is composed of two terms: (1) the ground terminal cost per minute (discussed above under Table C-6), and (2) the user's pro rata share of the space segment plus NCC cost (given in Table C-4). The formulas and data in this table is used to produce the total user costs given in Table C-8.

The "minutes use per year" is for the individual user. For example, operation for 1 hr/day, 250 working days per year, is 15,000 minutes use per year.

The "User annual traffic" is the number of bits transmitted in one year. For example, 15,000 minutes per year at 4 Mb/s would be 3.6×10^{12} bits in one year.

The "Total annual traffic" for the entire system equals the system utilization, times the system capacity in bits per second, times the number of seconds in a year. For example, the Mesh VSAT system utilization is 15% and capacity is 5.4 Gb/s. Since there are 3.16×10^7 seconds per year, "Total annual traffic" is 2.56×10^{16} bits or 26 Pb.

Table C-8: "Comparison of User Costs" gives the cost per minute for different circuit sizes, for shared ground terminal use. The formulas and data from Table C-8 are used to produce the total user costs in this table.

Consider for example the Mesh VSAT system. The $4.62 cost/min is for a duplex circuit at 4 Mb/s (costs for two ground terminals plus two simplex circuits). The $9.13 cost to transmit 1 Gb is for two ground terminals and one simplex 4 Mb/s circuit (it would take 250 seconds or 4.2 minutes of terminal time).

The cost per minute for a duplex circuit include use of two ground terminals plus two simplex circuits at the designated rate. The assumed terminal use per year is 4 hours per day, 250 working days per year (1,000 hours or 60,000 minutes per year). For circuits of size smaller than nominal (i. e., less than 4 Mb/s for the Mesh VSAT system), it is assumed that the ground terminal capacity and cost are shared among multiple users. For example, two 2-Mb/s users are sharing the costs of the 4-Mb/s Mesh VSAT ground terminals.

C.3 Cost Conclusions and Drivers

It is clear from Table C-8 that the B-ISDN system, Architecture 2 in particular, has approximately 4 times lower cost than the Mesh VSAT or Integrated Video systems. One reason is the 1.33 times higher system utilization (20% versus 15%) which is justified by the argument that it is easier to share capacity with B-ISDN. However, the main reason is the much higher system capacity due to the use of small spot beams ($0.4°$ versus $1°$). This conserves satellite downlink power and allows more capacity from the same mass satellite.

A number of cost conclusions can be drawn:

- Utilization assumptions are a key cost driver.
- Sharing of circuit capacity can have a large effect on effective rates. Some concepts such as B-ISDN have greater potential for circuit sharing.

- TDMA (hopping spot beam) has better potential for making capacity available to users.
- Spot beam size is the key cost driver. Limit on spot beam size is imposed by antenna size and baseband switch size. Switch architecture to accommodate 100 inputs and 100 outputs is difficult.
- Ground terminal costs are not significant except for the smallest circuits or else when the terminal is used a small number of hours per year.
- B-ISDN performs well due to its large circuit size and small spot beams.

System cost drivers can be summarized as follows:

Costs:

- Space segment costs (only pay for capacity used).
- Ground terminal costs (share fixed yearly cost among many users).

System Utilization:

- Assumed to be 15% to 20%.

System Capacity:

- Improved by increases in spacecraft payload to orbit.
- Better bus performance for payload mass and available power.
- Payload limited by available downlink transmit power.
- Use of smaller spot beams (larger antenna and/or higher frequency) conserves downlink power and allows more capacity in same mass.
- Switch imposes connectivity limit on number of spot beams.
- Use of TDMA on downlink can lessen connectivity problem.

Table C–1: Comparison of System Designs

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video
Satellite Parameters				
Mass, wet	1,890 kg	1,860 kg	1,770 kg	1,890 kg
DC power, end-of-life	5.6 kW	5.1 kW	3.5 kW	4.3 kW
RF transmit power	1,200 W	1,280 W	480 W	640 W
Baseband switch type	FO bus	IF	Crossbar	FO bus
Baseband processor power	870 W	—	606 W	874 W
Uplink spot beam size	2°x 4°	1.6°	0.4°	0.9°
Receive antenna size	0.6 m	1.4 m	1.8 m	0.8 m
Downlink spot beam size	1°	1.6°	0.4°	0.9°
Transmit antenna size	1.1 m	2.2 m	2.7 m	1.2 m
Transmit power/channel	30 W	32 W	40 W	13 W
Channel size (space-earth)	68 Mb/s	155 Mb/s	800 Mb/s	54 Mb/s
Ground Terminal Parameters				
Number of terminals	8,000	500	2,000	10,000
Terminal size (m)	1.8 & 3 m	3.1 m	3.0 m	1.2, 1.8, 3 m
Transmit power/channel	20 to 60 W	140 W	40 W	4 to 20 W
Channel size (earth-space)	4 Mb/s	155 Mb/s	200 Mb/s	2 or 6 Mb/s
System Parameters				
Simplex circuit capacity	5.3 Gb/s	12.4 Gb/s	19.2 Gb/s	5.3 Gb/s
Utilization	15 %	15%	20%	15%

Table C–2: Downlink Performance Comparison

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video
Transmit power/channel	30 W	32 W	40 W	13 W
EIRP (edge of coverage)	40.4 dBW	50.5 dBW	63.3 dBW	51.6 dBW
Data rate	68 Mb/s	155 Mb/s	800 Mb/s	54 Mb/s
Required bit error rate	10(-10)	10(-10)	10(-10)	10(-6)
Modulation	QPSK	8PSK	8PSK	BPSK
Coding type	Viterbi	Concat.	Concat.	Viterbi
Code rate	0.50	0.78	0.78	0.50
Coding gain	5.7 dB	11.2 dB	11.2 dB	5.3 dB
Assumed C/I	16 dB	20 dB	16 dB	16 dB
Interference degradation	1.8 dB	2.0 dB	4.0 dB	1.1 dB
Modem loss	1.5 dB	2.5 dB	2.5 dB	1.0 dB
Required Eb/No	13.1 dB	16.7 dB	16.7 dB	10.5 dB
Req'd. C/No – Data rate	13.7 dB-Hz	10.5 dB-Hz	15.0 dB-Hz	10.3 dB-Hz
Rain margin (dB)	3.1 dB	1.4 dB	5.7 dB	1.4 - 5.7 dB
Availability, Region E	99%	98%	99.5%	98 to 99.5%

Table C–3: Uplink Performance Comparison

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video
VSAT diameter	1.8 & 3 m	3.1 m	3 m	1.2, 1.8, 3 m
Transmit power/channel	26 W	140 W	8-18 W	4 - 12 W
EIRP	52.8 dBW	77.5 dBW	65.1+ dBW	53.7+ dBW
Data rate	4 Mb/s	155 Mb/s	200 Mb/s	2 - 6 Mb/s
Required bit error rate	10(-8)	10(-10)	10(-10)	10(-6)
Modulation	D-QPSK	8PSK	QPSK	D-QPSK
Coding type	Viterbi	Concat.	Block	Viterbi
Code rate	0.50	0.78	0.75	0.50
Coding gain	5.5 dB	—	6.0 dB	5.3 dB
Assumed C/I	16 dB	END-	20 dB	16 dB
Interference degradation	1.8 dB	-TO-	1.0 dB	1.1 dB
Modem loss	1.5 dB	-END	2.0 dB	1.0 dB
Required Eb/No	14.3 dB	LINK	13.1 dB	13.2 dB
Req'd. C/No – Data rate	15.1 dB-Hz	—	13.1 dB-Hz	14.8 dB-Hz
Rain margin (dB)	3.1 dB	3.1 dB	3.1 - 6.5 dB	3 - 12 dB
Availability, Region E	98%	98%	98 to 99%	98 to 99.5%

Table C–4: Space plus Network Control Costs

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video
Space Segment Costs				
Satellites (2)	$ 560 M	$ 443 M	$ 663 M	$ 560 M
Launches (2)	$ 248 M	$ 248 M	$ 248 M	$ 248 M
TT&C support (2)	$ 15 M	$ 15 M	$ 15 M	$ 15 M
Launch insurance (16%)	$ 157 M	$ 134 M	$ 176 M	$ 157 M
	$ 980 M	$ 840 M	$ 1,102 M	$ 980 M
Annual cost (15 yr @ 18%)	$ 192 M	$ 164 M	$ 216 M	$ 192 M
Network Control Costs				
NCC capital cost	$ 100 M	$ 100 M	$ 100 M	$ 100 M
NCC annual cost	$ 20 M	$ 20 M	$ 20 M	$ 20 M
O & M annual cost	$ 4 M	$ 4 M	$ 8 M	$ 4 M
	$ 24 M	$ 24 M	$ 28 M	$ 24 M
Space plus NCC Cost				
Total annual cost	$ 216 M	$ 188 M	$ 244 M	$ 216 M
Ground Terminal Costs				
Total terminal capital cost	$ 380 M	$ 50 M	$ 160 M	$ 400 M
Total terminal annual cost	$ 114 M	$ 15 M	$ 48 M	$ 120 M

Table C–5: Space plus Network Control Costs per Minute

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video
Space plus NCC Cost				
Total annual cost (2)	$216 M	$ 188 M	$ 244 M	$ 216 M
Satellite Capacity (2)	5.4 Gb/s	12.4 Gb/s	19.2 Gb/s	5.3 Gb/s
Satellite Utilization	15%	15%	20%	15%
Cost per Gb/s per minute of use (simplex circuit)	$507/min	$192/min	$121/min	$517/min
Cost per Gb transmitted	$8.45	$3.20	$2.02	$8.62

Table C–6: Ground Terminal Cost Comparison

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video
1.2 m Terminal				
Capital cost	—	—	—	$35,000
Annual cost (plus O&M)				$10,500
Cost per minute operation				
• 1 hr/day				$0.70/min
• 8 hr/day				$0.09/min
1.8 m Terminal				
Capital cost	$45,000	—	—	$45,000
Annual cost (plus O&M)	$13,500			$13,500
Cost per minute operation				
• 1 hr/day	$0.90/min			$0.90/min
• 8 hr/day	$0.11/min			$0.11/min
3 m Terminal				
Capital cost	$55,000	$100,000	$80,000	$55,000
Annual cost (plus O&M)	$16,500	$ 30,000	$24,000	$16,500
Cost per minute operation				
• 1 hr/day	$1.10/min	$2.00/min	$1.60/min	$1.10/min
• 8 hr/day	$0.14/min	$0.25/min	$0.20/min	$0.14/min

Table C–7: Cost Formulas and Values for 4 Satellite System Concepts

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video	
Circuit size	**4 Mb/s**	**155 Mb/s**	**155 Mb/s**	**2 Mb/s**	**6 Mb/s**
Ground terminal size	**1.8 m**	**3.1 m**	**3.0 m**	**1.2 m**	**1.8 m**
Ground terminal annual $	**$13,500**	**$30,000**	**$24,000**	**$10,500**	**$13,500**
Space segment annual $	**$216 M**	**$188 M**	**$244 M**	**$216 M**	
System utilization	**15%**	**15%**	**20%**	**15%**	
System capacity (2 sats)	**5.4 Gb/s**	**12.4 Gb/s**	**19.2 Gb/s**	**5.3 Gb/s**	
Total annual traffic*	**26 Pb**	**59 Pb**	**121 Pb**	**25 Pb**	

*** 1 Pb = 10(+15) bits**

$$\text{\$/min} = \frac{\text{Ground terminal annual \$}}{\text{minutes use per year}} + \frac{\text{Space segment annual \$}}{\text{minutes use per year}} \times \frac{\text{User annual traffic}}{\text{Total annual traffic}}$$

Total annual traffic = System utilization x System Capacity x seconds/year

Table C–8: Comparison of User Costs

	Mesh VSAT	B-ISDN Arch. 1	B-ISDN Arch. 2	Integrated Video	
Circuit size	**4 Mb/s**	**155 Mb/s**	**155 Mb/s**	**2 Mb/s**	**6 Mb/s**
Cost/min, duplex circuit*	**$4.62**	**$60.58**	**$38.24**	**$2.46**	**$6.78**
Cost per Gbit transmit †	**$9.13**	**$3.42**	**$2.18**	**$10.25**	**$9.42**
Cost/min, duplex circuit‡					
128 kb/s	**$0.14**	**$0.05**	**$0.03**	**$0.15**	**$0.14**
512 kb/s	**$0.58**	**$0.20**	**$0.13**	**$0.62**	**$0.57**
2 Mb/s	**$2.32**	**$0.80**	**$0.51**	**$2.46**	**$2.26**
4 Mb/s	**$4.62**	**$1.60**	**$1.02**	**—**	**$4.52**
6 Mb/s	**—**	**$2.35**	**$1.53**	**—**	**$6.78**

*** Duplex circuit includes 2 terminals and two-way circuit,**
† Simplex circuit includes 2 terminals and one-way circuit.
‡ Assumes use of 4 hour per day, 250 days per year; and sharing of terminals by multiple circuits where possible.

Appendix D

AIAA-92-2054-CP

Technical and Economic Feasibility of Integrated Video Service by Satellite†

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Abstract

Point-point video services, such as videophone, and point-to-multipoint video services, such as video conferencing, have been the subject of several overly optimistic technology forecasts. Though technically feasible, and to an extent operational today, neither service has met with widespread user acceptance. Two of the reasons for the deficiency are cost and user unfriendliness. With the availability of wideband fiber networks and the advent of high-power, intelligent satellites such as the NASA Advanced Communication Technology Satellite (ACTS), it may be feasible to circumvent these two deficiencies.

This paper presents the results of a feasibility study of using modern satellite technology, or more advanced technology, to create a cost-effective, user-friendly, integrated video service, which can provide videophone, video conference, or other equivalent wideband service on demand. A system is described which enables a user to select a desired audience and establish the necessary links in much the same way one would establish a teleconference by phone.

The paper is divided into five sections:

1. Video Standards
2. Video Traffic Scenarios
3. Satellite System Architecture
4. User Costs
5. Conclusions

1 Video Standards

A survey was carried out to examine existing video standards and the evolving standards for videoconference codecs in order to make technology assessments on the realization of various video services.

1.1 Current Standards

Both satellite and digital transmission capabilities are used for support of videoconferences. Business television services use the same standard video signals and transmission techniques now used for program distribution and electronic newsgathering by the networks. Digital videoconference codecs use transmission rates at or below 2.048 Mb/s. Rates from 384 kb/s to 2.048 Mb/s are used by motion codecs suitable for small groups, and rates of 56 kb/s to 128 kb/s are commonly used for individuals [Reference 1].

Several manufacturers now offer dual codecs that conform to CCITT Recommendation H.261, and optionally provide a proprietary coding technique [2]. The evolving videoconference standard for small groups seems likely to become n $\times$ 384 kb/s (where n is from 1 to 5) [3]. The evolving standard for personal teleconferences is 56 kb/s to 128 kb/s, and is expected to be widely used as the 2B+D ISDN service becomes available.

1.2 Teleconference Components

A videoconference is generally a two-way service with the capability of transmitting live or static pictures and associated speech, and may include more than two locations. Figure 1 shows the minimum equipment involved in a videoconference with two sites. Each site is equipped with a camera, monitor, microphone, and speaker. CCITT Recommendation H.100 describes basic facilities that should be included in terminal design [4].

There is currently considerable interest in moderate rate coders for use in either DBS (direct broadcast satellites) or in cable distribution. Both DBS and cable systems want to increase the number of channels that can be received, and to reduce problems with received noise or multipath reception. In time, these will result in inexpensive equipment capable of increased spatial and temporal resolution [compared to the low rate codecs]. The 1990 costs per hour for digital transmission facilities is shown in Figure 2 [5]. This shows the cost advantages of switched 56 kb/s transmission facilities which are four times less expensive than the dedicated (or leased line) of the same speed.

† This paper is based upon work sponsored by the National Aeronautics and Space Administration under contract NAS3-25092.

‡ Member, AIAA.

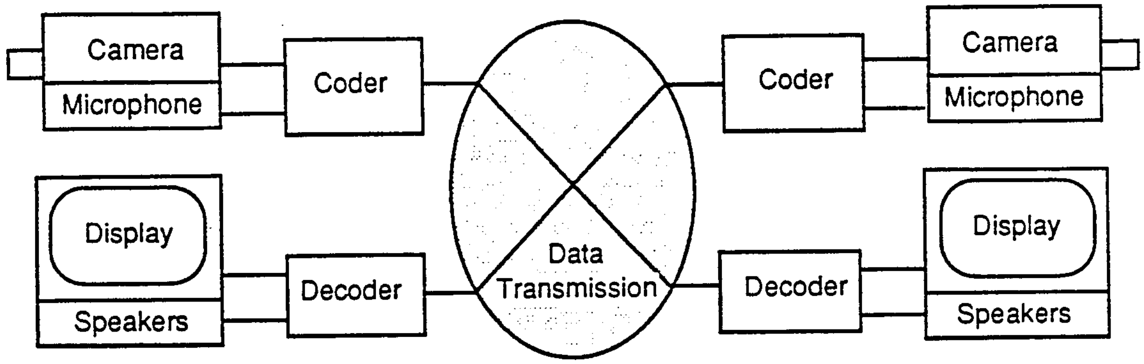

Figure 1: Basic Teleconference Equipment

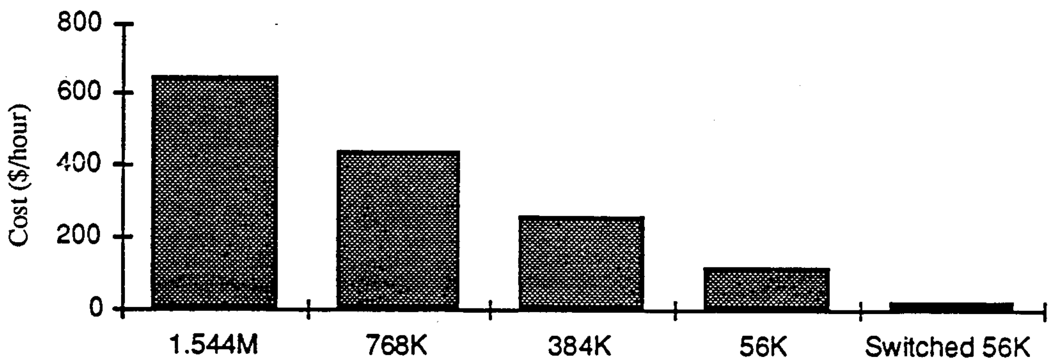

Figure 2: Cost ($/hour) Versus Digital Transmission Rate

1.3 Future Equipment and Standards

Videoconference codecs will continue to gradually improve in quality and prices will continue to decline. The biggest change is expected to be in lower prices due in large part to VLSI and high speed digital signal processing chip development. ISDN and B-ISDN will also bring changes due to increased customer access to higher rate digital channels. Three videoconference quality levels can be expected to evolve.

56 kb/s to 128 kb/s. ISDN will make the basic access 2B (128 kb/s) service widely available. Videoconferences involving a few people will be able to use this service. It will support reduced resolution motion video, and higher resolution still and graphics. Higher resolution displays that show several channels in separate windows are expected to be developed.

n x 384 kb/s will continue to be the primary service for small groups (6 to 10 people at each site). The increased bit rate allows higher resolution motion video and improved audio channel bandwidth. Codec manufacturers will eventually cross license improved coding for incorporation into the standard.

Business Television. DBS development work will produce codecs with higher performance than is currently available. Spatial and temporal resolution will approach broadcast quality at rates between 2 and 8 Mb/s.

The large number of different standards currently found will disappear. Customers will require adherence to widely accepted standards to increase the number of other locations that can be reached with visual communications.

2 Video Traffic Scenarios

Viable video traffic scenarios via satellite include both fully connected point-to-point as well as point-to-multipoint services.

2.1 Point-to-Point Traffic

The point-to-point traffic is expected to resemble present day business voice traffic in terms of physical location of users and distribution of traffic in time. Users are expected to be businesses, and traffic will follow the business day with morning and afternoon peaks. Users will desire different grades of service, which requires use of different amounts of bandwidth. This service is expected to be offered by terrestrial carriers via ISDN. However, there should be a certain percentage of satellite addressable traffic due to non-ISDN location of users.

Most of the traffic volume is expected to be narrowband ISDN basic service (up to 144 kb/s), with occasional users of primary access service (up to 1.544 Mb/s). Bandwidth of 64 to 128 kb/s should be sufficient for video of the participants, graphic display of images, and audio.

2.2 Point-to-Multipoint Traffic

Point-to-multipoint traffic is also expected to be primarily business, but with a significant component due to other groups such as religious, educational, remote buying, and specialty sporting events. The traffic will be more distributed in time, covering both business and leisure time.

Traffic will follow the general population, with the satellite addressable component perhaps avoiding the cities where high bandwidth cable to the home is more likely to be available. Most of the traffic will require ISDN primary access (up to 1.544 Mb/s), with a certain component demanding higher bandwidth (up to 6 Mb/s) for higher quality presentations.

3 Satellite System Architecture

3.1 System Configuration

The satellite system architecture supplies full mesh point-to-point and point-to-multipoint connections from a geosynchronous satellite at Ka-band, with the support of transmission rates (64 kb/s – 6 Mb/s) defined for emerging video telephone and video conference standards through small terminals. The architecture employs a fixed spot beam coverage pattern and an on-board baseband processor that performs demultiplexing, demodulation, switching, and remodulation. Twenty-eight uplink and downlink spot beams of 0.87° provide CONUS coverage, with symmetric uplink and downlink beam patterns. Isolation is provided through frequency reuse and augmented by cross-polarization techniques. Due to the bandwidth requirements of the system, Ka-band was selected.

A multi-frequency TDMA (MF/TDMA) access scheme provides flexible and efficient utilization of the uplink bandwidth. Users may access the network through carriers of 2 Mb/s or 6 Mb/s, which can be time-shared among several users with low throughput requirements or used as a single TDM transmission rate from one earth station. Each beam area is dynamically assigned bandwidth in blocks of 50 MHz containing information rates of 36 Mb/s. This 36 Mb/s rate is divided into either eighteen 2 Mb/s carriers or six 6 Mb/s carriers. Up to four blocks of 50 MHz may be assigned to any beam. For the downlinks, transmission is TDM with carrier bit rates of 36 Mb/s. Between

Table 1: System Design Parameters

System Parameters	Uplink	Downlink
Number of beams	28	28
Access	MF/TDMA	TDM
Modulation	QPSK	QPSK
FEC code rate	0.50	0.50
Information rate/beam	36-144 Mb/s	36-144 Mb/s
Bandwidth/beam	200 MHz	200 MHz
System bandwidth req'd	1.4 GHz	1.4 GHz
Carrier info. bit rate	2 or 6 Mb/s	36 Mb/s
Max. no. carriers/beam	72	4
Total no. carriers	768	64
System capacity	2.3 Gb/s	2.3 Gb/s

one and four 36 Mb/s carriers may be dynamically assigned to any spot beam. The total system information capacity is 2.3 Gb/s.

A rate 1/2 convolution code is assumed for both uplink and downlink transmissions. In addition, differential encoding is used on the uplinks to simplify onboard hardware for carrier phase ambiguity resolution. Differential encoding is not used for downlinks. QPSK modulation is used on both the uplink and downlink. The combination of a (maximum) 144 Mb/s information rate, rate 1/2 FEC coding, and QPSK modulation yields a beam bandwidth requirement of 200 MHz, based on a Nyquist rolloff of 33%. With a frequency reuse factor of 7, a system bandwidth of 1.4 GHz is required for both the uplink and downlink transmissions. Table 1 summarizes the system design parameters.

The network supports small earth stations, ranging in size from 1.2 m to 3 m with an amplifier of 4 W to 40 W per carrier. Transmit power or earth station size can be increased to combat rain fade in certain areas. For example, a 2 m terminal with a 10 W amplifier will provide 99.5% availability in rain region D. The satellite amplifiers require an output of 15 W per 36 Mb/s carrier.

Capacity allocation and network management is divided between an on-board network controller and a network control station located in one of the beams. This station could also serve as the TT&C site for the spacecraft. The network control station assigns capacity to requesting earth stations on the basis of available carriers and on-board buffer occupancy. It is also responsible for routing information needed to route traffic through the network.

3.2 Baseband Processor

Figure 3 shows a functional block diagram of the on-board baseband processor. Certain aspects of the processor design are drawn from [6]. The basic functions performed by the on-board processor include the following:

- Demultiplexing and demodulation of the uplink carriers via digital multicarrier demodulators (MCDs);

- Descrambling, decoding and formatting for baseband switching of the incoming coded data by the input processors;

- Switching of the baseband data via a baseband switch fabric;

- Output buffering and frame assembly by the output processors;

- Modulation and multiplexing the carriers for downlink transmission;

- Control of the processor including monitoring and controlling of the processor subsystems and interfacing between the network control station and the user earth stations for signaling and routing purposes.

The on-board processor is centered around a 2.5 Gb/s TDM optical ring which interfaces to the input and output processing units. Although this design could be used as the fabric of a circuit-switched architecture, for this system the ring is used as a self-routing, strictly non-blocking fast packet switch for routing simplicity. In addition to the self-routing capability, this particular switch design is advantageous for several other reasons, including and inherent multicase topology, a simple interface among processing units, and a modular design for flexibility and fault-tolerance.

Both circuit-switched and packet-switched data can be accommodated by the system through the use of satellite virtual packets (SVPs). Packets are assembled at the earth station in a 1024-bit structure which contains an information field of 960 bits and a 64-bit header. This header is used by the baseband switch and the destination earth station for routing purposes. The output processors on the optical ring are able to filter packets based on the examination of two bits in each header, while downlink traffic can be sorted at the earth stations on the basis of destination addresses within the header. SVP headers are assigned to earth stations at the time of a call setup by the network control station; all traffic for a particular connection is thereby assigned the same header.

3.3 Frame Structures of Data

All traffic on the satellite link is packetized to simplify on-board routing procedures. These packets are assembled at the source earth station and placed within a uplink TDMA frame structure. A basic depiction of the TDMA frame is illustrated in Figure 4. These frame structures accommodate traffic at integer multiples of 64 kb/s. The use of a packet switched architecture provides simpler uplink time slot allocation and eliminates the need for coordinated time plan changes.

The uplink frame is 15 ms and consists of either 32 or 96 time slots, depending on the uplink carrier bit rate. Each time slot contains one satellite virtual packet (SVP) of 1024 bits, with a resulting frame efficiency of approximately 94%. The 15 ms downlink TDM frame contains 576 time slots, each capable of supporting 64 kb/s.

3.4 Satellite Design

The satellite design is based on the current Space System/Loral 3-axis Intelsat VII bus plus evolutionary improvements appropriate to a year 2000 launch. Satellite dry mass is approximately 1,500 kg, which allows an Atlas 2AS launch. Sufficient fuel is carried for a 12-year life. End-of-life DC power is 4 kW, with 640 W RF transmit power at Ka-band. The baseband processor, including multi-carrier demodulators, consumes 1.0 kW power and has 121 kg mass.

3.4.1 Mass and Power Estimates of Satellite

Table 2 summarizes the mass budget (1,498 kg dry mass) and Table 3 summarizes the power budget (3.7 kW) for the satellite (assumed on-orbit in year 2000). There are 64 each 10-W Ka-band solid state transmitters with 32% assumed efficiency. The baseband processor includes multi-carrier demodulators, decoders, and modulators.

3.4.2 Mass and Power Estimates of Processor

The on-board baseband processor is a major component of the payload, and is estimated to have a mass of 121 kg and power consumption of 1.0 kW, based on implementation for year 2000 launch. The digital device technologies used are GaAs for high-speed processing, such as fiber optic interface processing, and high-density CMOS (HCMOS) for other processing functions. The GaAs device currently offers 0.1 mW of power/gate, 50,000 usable gate density, and a speed of up to 5 Gb/s. Radiation-hard HCMOS, on the other hand, offers 12 W/MHz of power/gate, 50,000 usable gate density, and a speed of up to 400 Mb/s. A 50% reduction in power/gate is assumed.

Most processing functions required in the design can be implemented with currently available technology and are regarded as low risk. The processing units identified for new development are a low-power consumption multi-carrier demodulator (MCD) for a transmission rate of 72 Mb/s, a 72 Mb/s multi-carrier decoder on a single chip, and a 16 K x 32 static RAM (SRAM). Based on these technology assumptions, the on-board baseband processor will consume about 1.0 kW of power and have a mass of 121 kg. The design includes the following elements:

- 64 MCDs, 32 for 2 Mb/s carriers and 32 for 6 Mb/s carriers;

- 32 input and output processors;

- Autonomous network controller, fully-redundant.

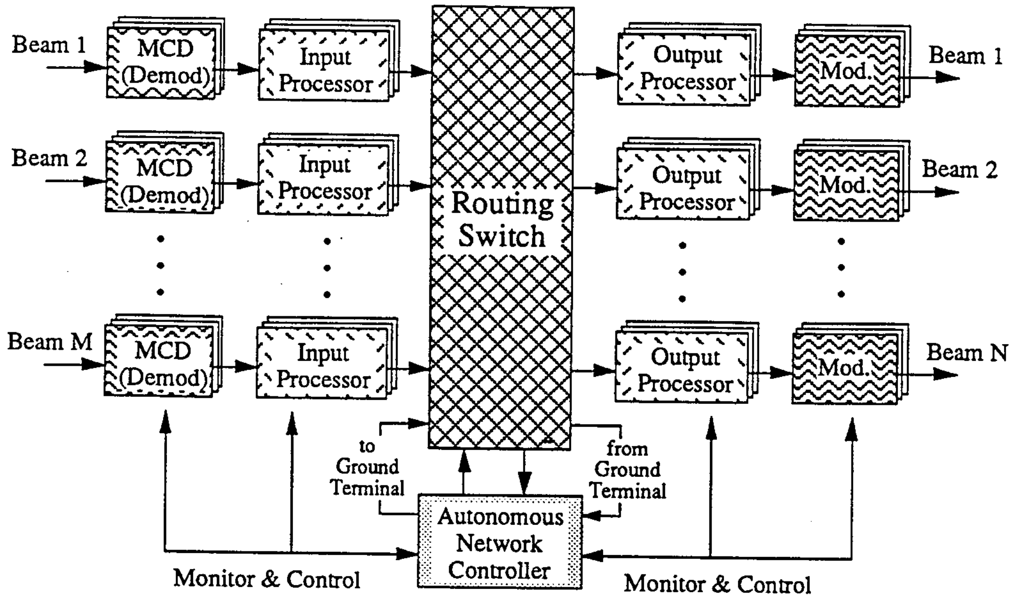

Figure 3: On-Board Processor Configuration

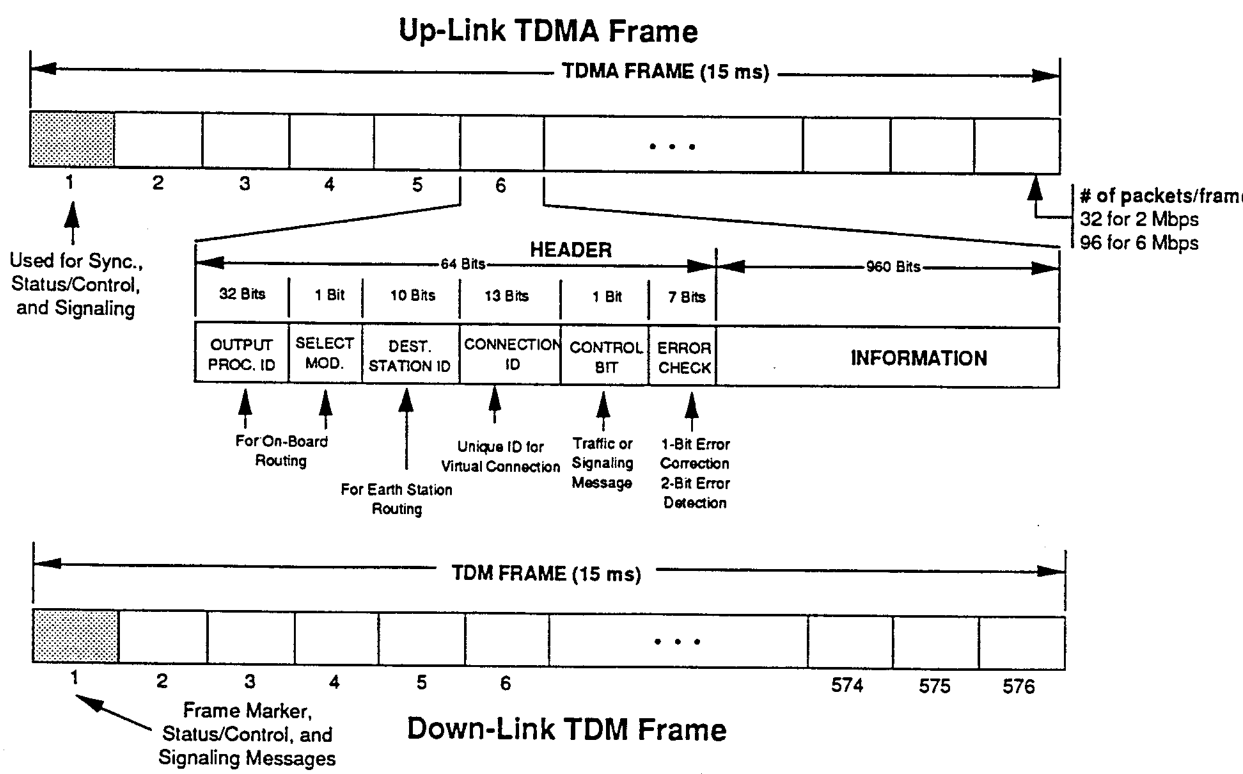

Figure 4: Uplink TDMA Frame Structure and Downlink TDM Frame Structure

Subsystem	Mass (kg)
Attitude control	140
TT&C	15
Power	310
Propulsion	110
Structure	220
Thermal	120
Payload – Antenna	50
– Electronics	403
Integration; elect. & mech.	120
Total (dry mass)	1,498
Fuel	2,164
Launch mass	3,662

Table 2: Satellite Mass Summary

Component	Power (W)	
Bus Subsystems		420
Battery Charging		180
Receivers		100
Baseband Processor:		
Multi-carrier demods	480	
Input/output processors	210	
Modulators	10	
Auto. network controller	30	
Power supply	270	
Subtotal	1,000	1,000
Transmitters		2,000
Total Satellite		3,700

Table 3: Satellite Power Summary

4 User Costs

System costs were estimated for an integrated video satellite system including satellites, ground terminals, and network control center. Table 4 summarizes the space segment costs in 1991 dollars for a commercial program consisting of two satellites with 12-year lifetimes beginning in the year 2000. The annualized cost for two on-orbit satellites is \$225 M per year, assuming 15% interest rate and a profit of \$75 M/year to the system operators. The network control center annualized cost is estimated at \$25 M/yr, giving a total of \$125 M/yr per satellite.

Usage of satellite communications capacity is assumed to be 15% of maximum (2.3 Gb/s) averaged over the year. This is equivalent to 4 hours/day full capacity for 260 working days in the year, or 1,040 hours per year of 2.3 Gb/s for one satellite (which has an annual cost of \$125 M/yr). Thus the basic space segment (including network control) cost is \$50.00/hr per Mb/s of capacity utilized. Space segment costs as a function of circuit size (simplex circuits) are as follows:

Table 4: Space Segment Costs, 1991 \$M

Cost Category (2 satellites on orbit)	Life Cycle Cost	Annual Cost at 15%
Satellite cost (2)	420 M	
Launch cost (2)	248 M	
TT&C support (2)	12 M	
Launch insurance (16%)	130 M	
Subtotal Cost	\$810 M	\$150 M/yr
Profit (50%/yr)		75 M/yr
Total Charges		\$225 M/yr

Table 5: User Terminal Costs (\$/minute)

Ground Terminal			Terminal Cost (\$/minute)			
	Max. Capac.	Annual Cost	No. hours used per day			
Size	Mb/s	\$K/yr	1	2	4	8
1.2 m	.144	3	0.20	0.10	0.05	0.03
1.8 m	6	9	0.60	0.30	0.15	0.08
3 m	6	12	0.80	0.40	0.20	0.10

\$3.20/hr	(5 cents per min.)	for 64 kb/s
\$6.40/hr	(11 cents per min.)	for 128 kb/s
\$12.80/hr	(21 cents per min.)	for 256 kb/s
\$25.60/hr	(43 cents per min.)	for 512 kb/s
\$38.40/hr	(64 cents per min.)	for 768 kb/s
\$75/hr	(\$1.25 per min.)	for 1.5 Mb/s
\$150/hr	(\$2.50 per min.)	for 3 Mb/s
\$300/hr	(\$5.00 per min.)	for 6 Mb/s

Table 5 summarizes ground terminal costs in \$/minute of use as a function of terminal type and number of hours utilized per working day (5 days per week, 260 days per year). Note that sharing of a ground terminal by several users has the potential to significantly reduce ground terminal costs by increasing utilization.

Table 6 combines space, network control, and ground segment costs to obtain total costs for duplex circuits (2 ground terminals and 2 simplex circuits). User ground terminals are assumed to be utilized 4 hr/day. Note that the cost of the ground terminal is very significant for the small user, but for the larger capacity user, the cost of the ground terminal is small. In general, the cost of communications varies directly as the bit rate.

5 Conclusions

5.1 Viability of Service

Important conclusions are as follows:

- Integrated video by satellite is technically and economically feasible by the year 2000. The service can

Table 6: Total Duplex Circuit Costs

Circuit Size	Ground Terminal Size	Ground Terminal Cost ($/min)	Space/ Control Cost ($/min)	Total Cost ($/min)
64 kb/s	1.2 m	$0.10	$0.10	$0.20
128 kb/s	1.2 m	$0.10	$0.22	$0.32
256 kb/s	1.8 m	$0.30	$0.43	$0.73
512 kb/s	1.8 m	$0.30	$0.85	$1.15
768 kb/s	1.8 m	$0.30	$1.28	$1.58
1.5 Mb/s	1.8 m	$0.30	$2.50	$2.80
3 Mb/s	3.0 m	$0.40	$5.00	$5.40
6 Mb/s	3.0 m	$0.40	$10.00	$10.40

be cost competitive with terrestrial circuits for certain applications.

- The system offers "service on demand" so that users can easily alter the channel bandwidth, the service quality, and the number of participating sites in accordance with the service needs while the video conference is in progress.

- User friendly systems which are compatible with terrestrial standards and systems are essential to develop a market for satellite integrated video applications.

- A number of technologies must be developed. These technologies are described in the next paragraph.

5.2 Critical Technologies

A number of technologies which are critical and/or enabling for the integrated video application have been identified.

Antenna technology for MMIC feeds or phased arrays to reduce mass. Use of higher strength materials in the antenna subsystem to reduce mass.

Antenna pointing of $0.87°$ spot beams may require use of a pilot beam. Technology for pointing smaller spot beams will be demonstrated by the ACTS program.

Adaptive rain fade compensation techniques such as those implemented for ACTS should be evaluated and improved for use in the Ka-band rain fade environment.

Multi-channel demodulators (MCDs) are the most critical technology for the realization of the on-board baseband processor. The capacity of a single unit, assuming rate 1/2 coding, is 72 Mb/s, consisting of either 6 or 18 fixed-rate carriers. MCD power consumption must be reduced since it accounts for over half as much power as the rest of the on-board processor. Because of high power consumption, a polyphase approach to digital demultiplexing [7] was used. This approach allows for reduced complexity if uniform carriers are used. Intensive development efforts to reduce the MCD power requirements are strongly recommended.

In the design, a bit synchronous system in the uplink carriers improves frame efficiency and simplifies onboard processor design as well as network control procedures. However, the MCD is required to measure a phase error with an accuracy of a small fraction of a symbol period. It also necessitates the user terminal to perform accurate timing correction. Alternate techniques to implement a bit synchronous system should be investigated.

Modulation and coding must be considered together for optimum design. A high speed (72 Mb/s) multicarrier decoder is required. Key issues are mass and power, and flexibility in using different modulation formats. Coding schemes should be realizable with codes of small mass and low power usage. Use of a higher rate code could be combined with binary modulation to achieve similar results, with the advantage of lower bit rate MCDs.

Power amplifiers. The improvement in efficiency of TWTAs and SSPAs needs to be continued. (We assume 32% efficiency for Ka-band SSPAs in our satellite design. Other key issues include linearity, 12 yr lifetime, and high power solid state devices. For the active aperture antennas with multiple beams, high power (1 W), linear MMIC devices are required at Ka-band.

Baseband Processor requires a high-speed optical bus interface.

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The trends and roles of satellite based video services in the year 2010 time frame are examined based on an overall network and service model for that period. Emphasis is placed on point to point and point to multipoint service, but broadcast could also be accommodated. An estimate of the video traffic is made and the service and general network requirements are identified. User charges are then estimated based on several usage scenarios. In order to accommodate these traffic needs, a 28 spot beam satellite architecture with on-board processing and signal routing is suggested.

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